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ADVANCED MATERIALS BY DESIGN

CONGRESS OF THE UNITED STATES   OFFICE OF TECHNOLOGY ASSESSMENT

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Foreword

This assessment responds to a joint request from the House Committee on Science, Space, and Technology and the Senate Committee on Commerce, Science, and Transportation to analyze the military and commercial opportunities presented by new structural materials technologies, and to outline the Federal policy objectives that are consistent with those opportunities.

New structural materials—ceramics, polymers, metals, or hybrid materials derived from these, called composites—open a promising avenue to renewed international competitiveness of U.S. manufacturing industries. There will be many opportunities for use of the materials in aerospace, automotive, industrial, medical, and construction applications in the next 25 years. This assessment addresses the impact of advanced structural materials on the competitiveness of the U.S. manufacturing sector, and offers policy options for accelerating the commercial utilization of the materials.

In recent years, several excellent studies have been published on both ceramics and polymer matrix composites. This assessment draws on this body of work and presents a broad picture of where these technologies stand today and where they are likely to go in the future. OTA appreciates the assistance provided by the contractors, advisory panel, and workshop participants, as well as the many reviewers whose comments helped to ensure the accuracy of the report.

John H Gibbons

JOHN H. GIBBONS
Director

Advanced Materials by Design Advisory Panel

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Center for Composite Materials
University of Delaware

NOTE: OTA appreciates the valuable assistance and thoughtful critiques provided by the advisory panel members. The panel does not, however, necessarily approve, disapprove, or endorse this assessment. OTA assumes full responsibility for the assessment and the accuracy of its contents.

OTA Project Staff for Advanced Materials by Design

Lionel S. Johns, *Assistant Director, OTA*
Energy, Materials, and International Security Division

Peter D. Blair, *Energy and Materials Program Manager*

Gregory Eyring, *Project Director, November 1985 - June 1988*

Laurie Evans Gavrin, *Analyst, June 1986 - June 1988*

Thomas E. Bull, *Project Director, June 1985 - November 1985*

Joan Adams, *Analyst, June 1985 - January 1986*

Administrative Staff

Lillian Chapman Linda Long Tina Brumfield

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Overview

New structural materials technologies will be a determining factor in the global competitiveness of U.S. manufacturing industries in the 1990s and beyond. Today, for instance, materials account for as much as 30 to 50 percent of the costs of most manufactured products. New materials that can reduce overall production costs and improve performance can provide a competitive edge in many products, including aircraft, automobiles, industrial machinery, and sporting goods.

Remarkable advances in structural materials technologies have been made in the past 25 years. New materials such as ceramics and composites offer superior properties (e.g., high-temperature strength, high stiffness, and light weight) compared with traditional metals such as steel and aluminum. What is more, the materials themselves can be designed to have the properties required by a given application. Use of such designed materials, which are often called "advanced," can lead to higher fuel efficiencies, lower assembly costs, and longer service life for many manufactured products.

Although the United States has achieved a strong position in advanced materials technologies, largely as a result of military programs, it is by no means certain that the United States will lead the world in the commercialization of these materials The technologies are still in their infancy, and cost-effective use of advanced materials and fabrication processes is yet to be demonstrated in large-scale commercial applications. Potential end users in the United States have adopted a "wait and see" attitude, pending the solution of remaining technical and economic problems. However, through well-coordinated government-industry efforts, several countries, notably Japan, have initiated more aggressive programs to commercialize their evolving materials technologies. These programs have succeeded in bringing advanced material products to the market years in advance of comparable U.S. products. Concern about the U.S. competitive position has led Congress to seek a coherent national program to ensure that the United States will be able to capitalize on the opportunities offered by advanced materials.

Advanced materials can be classified as metals, ceramics, polymers, or composites, which generally consist of fibers of one material held together by a matrix of a second material. Composites are designed so that the fibers provide strength, stiffness, and fracture toughness, and the matrix binds the fibers together in the proper orientation. This assessment focuses on three promising categories of structural materials: ceramics (including ceramic matrix composites), polymer matrix composites, and metal matrix composites. The principal purpose is to describe the major opportunities for use of ceramics and composites, and to identify steps that the Federal Government could take to accelerate the commercialization of advanced materials technologies in the United States.

THE U.S. ADVANCED MATERIALS ENVIRONMENT

The current value of components produced from advanced structural ceramics and composites in the United States is less than $2 billion per year. However, by the year 2000, U.S. production is expected to grow to nearly $20 billion. This estimate includes only the value of the materials and structures; it does not include the value of the finished products (e.g., aircraft and automobiles), whose performance, and therefore competitive posture, is improved by use of the materials. When the overall value of these products is taken into account, use of advanced structural materials is likely to have a dramatic impact on gross national product, balance of trade, and employment.

Military demand for high performance materials in the United States has already created a thriving community of advanced materials suppliers. These suppliers are also seeking commercial applications for their materials. At present, though, advanced materials developed for military applications are expensive, and fabrication processes are poorly suited for mass production.

Potential U.S. commercial end users believe that major use of these materials will not be profitable within the next 5 years, the typical planning horizon of most firms. In many cases, 10 to 20 years will be required to solve remaining technical problems and to develop rapid, low-cost manufacturing methods. Investment risks are especially high for commercial end users because the costs of scaling up laboratory processes for production are enormous, and the rapid pace of technology evolution could make these processes obsolete. Hence, there is very little commercial "market pull" on advanced materials technologies in the United States.

In contrast to the market pull orientation of firms in the United States, end users in foreign competitor nations, notably in Japan, are pursuing a "technology push" approach, in which near-term profits are sacrificed in favor of gaining the production experience necessary to secure a share of the large future markets. This aggressive approach will probably give these firms a significant advantage in exploiting global markets as they develop. OTA finds that manufacturing experience over time with advanced materials will be a prerequisite for competing in those markets; U.S. companies should not expect to be able to step in and produce competitive advanced materials products after the manufacturing problems have been solved by others.

THE ROLE OF THE FEDERAL GOVERNMENT

The Federal Government directly affects the development of advanced materials through funding of basic research, technology demonstration programs, and military and aerospace procurement of advanced materials and structures. The U.S. Government currently spends about $167 million per year for R&D on structural ceramics and composites, more than any other nation.

Counting only basic and early applied research, the Department of Defense (DoD) sponsors about 60 percent ($98 million) of this total. In the case of the military, the government itself is the customer for materials technology and hardware. Advanced materials are truly enabling technologies for many military systems such as the National Aerospace Plane, Stealth aircraft, and missiles; they can also enhance the mission capability of a host of less exotic systems such as tanks, ships, submarines, and ground vehicles. Transfer of DoD-funded materials technology to the commercial sector, however, is discouraged by two major factors. First, the high cost of military materials and fabrication processes limits their acceptance in the commercial sector. Second, to deny these advanced materials to the U.S.'s adversaries, the government imposes restrictions on the export of the materials and on access to related technical data.

About 40 percent ($69 million) of Federal spending for structural ceramics and composites R&D is nonmilitary in nature, including most of that funded by the Department of Energy, the National Aeronautics and Space Administration, the National Science Foundation, the National Bureau of Standards, and the Bureau of Mines. These agencies generally do not act as procurers of hardware. Rather, they sponsor materials research ranging from basic science to technology demonstration programs, according to their various mission objectives. Where appropriate, they openly seek to transfer materials technology to the private sector.

FOUR KEY POLICY OBJECTIVES

OTA's analysis suggests four key Federal policy objectives that could accelerate the commercialization of advanced materials technologies. Options for implementing these objectives range from those that have a broad scope, and affect many technologies, to those that specifically affect advanced materials technologies.

1. **Encourage potential end users to make long-term capital investments in advanced materials.**

Greater investment in advanced materials by potential end users would help to generate more commercial market pull on these materials in the United States. The climate for investment in long-term, high-risk technologies such as advanced materials could be improved by Federal Government implemention of a variety of policy options designed to make more patient investment capital available. These would include providing tax incentives for long-term capital investment, reducing taxes on personal savings, and changing tort law to make product liability proportional to proven negligence.

2. **Facilitate government/university/industry collaboration in R&D for low-cost materials fabrication.**

The high cost of advanced materials development and the small near-term markets are forcing companies to seek collaborative R&D arrangements to spread the risks and raise the large amounts of capital required. Three major reservoirs of materials expertise are available to U.S. companies: 1) universities, 2) Federal laboratories, and 3) small high-technology firms. Among industry/university and industry/Federal laboratory collaborative centers in advanced materials, OTA finds that industry generally participates to gain access to new ideas and trained graduate students. At present, industry considers the scale-up costs too high and the payoffs too uncertain to justify commercialization of collaborative research results. The government could encourage the commercialization step by establishing collaborative centers in which government and industry would share the costs of downstream materials fabrication technology development. Another option would be to provide incentives for large companies to work with those small, high technology firms that have advanced materials fabrication expertise, but lack the capital to explore its commercial potential.

3. **Facilitate more effective commercial exploitation of military R&D investments where possible.**

In the next 5 to 10 years, military demand for advanced materials is likely to grow at a faster pace than commercial demand, so that military policies and requirements will strongly influence the agenda for advanced materials development in the United States. It is evident that government restrictions on advanced materials and associated technical data in the interests of national security can cause conflict with U.S.-based firms seeking unrestricted access to markets and information. Furthermore, these conflicts are likely to become more severe as commercial applications grow and as the companies involved become more multinational.

Ultimately, both national security and a competitive manufacturing base will depend on a strong domestic advanced materials capability. Therefore, a major goal of U.S. policy should be to strike an appropriate balance between military and commercial interests. Among the options that could be considered are: updating export control lists so that they are applied only to technologies that provide important military advantage to the United States and that are not available to our adversaries from other sources; greater support for military programs aimed at developing low-cost materials fabrication processes that could be adapted for commercial use; and clarification of military domestic sourcing policies for advanced materials.

4. **Build a strong advanced materials technology infrastructure.**

Through acquisitions, joint ventures, and licensing agreements, materials technology is flowing rapidly among firms and across national borders. Critical advances continue to come from abroad, and the flow of materials technology into the United States may already be as important as that flowing out. It is essential that an adequate technology infrastructure be in place for rapidly capitalizing on research results, whether they originate in the United States or abroad. Policy options for building up this infrastructure include: increasing funding for research on reliable, low-cost manufacturing methods; gathering and disseminating information on foreign and domestic research efforts; accelerating development of materials testing standards and materials property databases for designers; and increasing support for multidisciplinary materials engineering programs in universities and for retraining of engineers in the field who are unfamiliar with the new materials.

TWO VIEWS OF ADVANCED MATERIALS POLICIES

Congress and the Administration have adopted conflicting views of policymaking with regard to advanced materials. The crux of the conflict is whether the Federal Government should adopt a national plan for advanced materials technology development, or whether goals and priorities should be established in a decentralized fashion according to the different missions of the principal funding agencies.

According to the congressional view, national goals and priorities should be established above the agency level, and agency spending on materials programs should be made consistent with them. This view is expressed in the National Critical Materials Act of 1984, in which Congress established the National Critical Materials Council (NCMC) in the Executive Office of the President. The NCMC is charged with the responsibility of working with the principal funding agencies and the Office of Management and Budget to define national priorities for materials R&D and to coordinate the various agency efforts.

In the Administration's view, priorities for advanced materials R&D cannot be separated from the functional requirements of the structures in which they are used. Because different agencies have different requirements for materials, determination of R&D priorities is best made at the agency level. Strategic advanced materials planning is seen as putting the government in a position of "picking winners"—a role that is best left to the private sector. According to this view, the Office of Science and Technology Policy's Committee on Materials (COMAT), and other interagency committees, which meet to exchange information about ongoing advanced materials projects and budgets, are adequate for avoiding excessive duplication and waste. The NCMC is considered redundant with these committees.

OTA finds that it is more difficult to define national policy goals for advanced materials than for more traditional critical materials. To succeed in its task, the NCMC will need to establish a more precise definition of the goals that would motivate such a national materials policy, as well as to develop high-level Administration commitment to the concept of such a policy.

Pending the resolution of these differences, there are three further functions that the NCMC could perform. First, it could serve as a point of contact for monitoring industry concerns and recommendations regarding joint industry/government initiatives. Second, it could gather information on domestic and foreign materials R&D efforts and disseminate it to industry. Third, it could act as a broker for resolving conflicts between military and commercial agency goals for advanced materials.

ADVANCED MATERIALS POLICIES IN A BROADER CONTEXT

In many respects, the competitive challenges facing advanced materials are a microcosm of the challenges facing the U.S. manufacturing sector as a whole. Therefore, advanced materials policy cannot be viewed as a wholly separate issue. Policy options such as tax incentives for long-term capital investments or revision of export controls could also serve to stimulate a broad range of other technologies. Such policy options cannot be adequately addressed at the agency level or in interagency committees; they clearly must be initiated in the highest councils of government. Advanced materials policies therefore, can most effectively be treated as one facet of a high-level, high-priority policy of strengthening the Nation's entire industrial and manufacturing base.

Chapter 1

Executive Summary

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Chapter 1

Executive Summary

INTRODUCTION

During the past 25 years, unprecedented progress has been made in the development of new structural materials. These materials, which include advanced ceramics, polymers, metals, and hybrid materials derived from these, called composites, open up new engineering possibilities for the designer. Their superior properties, such as the high temperature strength of ceramics or the high stiffness and light weight of composites, offer the opportunity for more compact designs, greater fuel efficiency, and longer service life in a wide variety of products, from sports equipment to high performance aircraft. In addition, these materials can lead to entirely new military and commercial applications that would not be feasible with conventional materials. A graphic example is the construction of the composite airplane Voyager, which flew nonstop around the world in December 1986.

In the next 25 years, new structural materials will provide a powerful leverage point for the manufacturing sector of the economy: not only can ceramic and composite components deliver superior performance, they also enhance the performance and value of the larger systems—e.g., aircraft and automobiles—in which they are incorporated. Given this multiplier effect, it is likely that the application of advanced structural materials will have a dramatic impact on gross national product, balance of trade, and employment in the United States. All of the industrialized countries have recognized these opportunities and are competing actively for shares of the large commercial and military markets at stake.

As indicated in table 1-1, Congress has long been concerned with materials issues, dating back to the Strategic War Materials Act of 1939. Through the 1950s, legislation continued to focus on ensuring access to reliable supplies of strategic materials in time of national emergency. The 1970s saw legislative interest broaden to include the economic and environmental implications of the entire materials cycle, from mining to disposal.

Table 1-1.—U.S. Materials and Minerals Legislation

Strategic War Materials Act—1939
53 Stat. 811
Established the National Defense Stockpile, intended to accumulate a 5-year supply of critical materials for use in wartime or national emergency.

Strategic and Critical Materials Stockpiling Act—1946
60 Stat. 596
Authorized appropriation of money to acquire metals, oils, rubber, fibers, and other materials needed in wartime.

Defense Production Act—1950
64 Stat. 798
Authorized the President to allocate materials and facilities for defense production, to make and guarantee loans to expand defense production, and to enter into long-term supply contracts for scarce materials.

Resource Recovery Act—1970
Public Law 91-512
Established the National Commission on Materials Policy to develop a national materials policy, including supply, use, recovery, and disposal of materials.

Mining and Minerals Policy Act—1970
Public Law 91-631
Encouraged the Secretary of the Interior to promote involvement of private enterprise in economic development, mining disposal, and reclamation of materials.

Strategic and Critical Stockpiling Revision Act—1979
Public Law 96-41
Changed stockpile supply period to 3 years, limited to national defense needs only; established a stockpile transaction fund.

National Materials Policy, Research and Development Act—1980
Public Law 96-479
Directed the President to assess material demand, supplies, and needs for the economy and national security; and to submit a program plan to implement the findings of the assessment.

National Critical Materials Act—1984
Public Law 98-373
Established the National Critical Materials Council in the Executive Office of the President; the Council was authorized to oversee the development of policies relating to both critical and advanced materials; and to develop a program for implementing these policies.

SOURCE: Office of Technology Assessment, 1988.

In 1984, these concerns were extended to encompass advanced materials with the National Critical Materials Act (Public Law 98-373, Title II). In this Act, Congress established the National Critical Materials Council in the Executive Office of the President and charged it with the responsibility of overseeing the formulation of policies relating to both "critical" and "advanced" materials. The intent was to establish a policy focus above the agency level to set responsibilities for developing materials policies, and to coordinate the materials R&D programs of the relevant agencies.

With the passage of the National Critical Materials Act, Congress formally recognized that a domestic advanced materials manufacturing base will be critical for both U.S. industrial competitiveness and a strong national defense, and that progress in achieving this objective will be strongly influenced by Federal policies. Congressional interest in advanced materials technologies has centered on several key issues:

1. What are the major potential opportunities for advanced structural materials, and what factors will affect the time required to realize these opportunities?
2. What will be the impact of advanced materials on manufacturing industries in the United States?
3. What is the competitive position of the United States in these technologies, and what trends are likely to affect this position?
4. How can the federally funded advanced materials R&D in universities and Federal laboratories be used more effectively to boost the competitiveness of U.S. firms?
5. What are the implications of the large military role in advanced materials development for the commercial sector?
6. What policy options does the Federal Government have to accelerate the commercialization of advanced materials technologies?

These questions comprise the framework of this assessment.

NEW STRUCTURAL MATERIALS

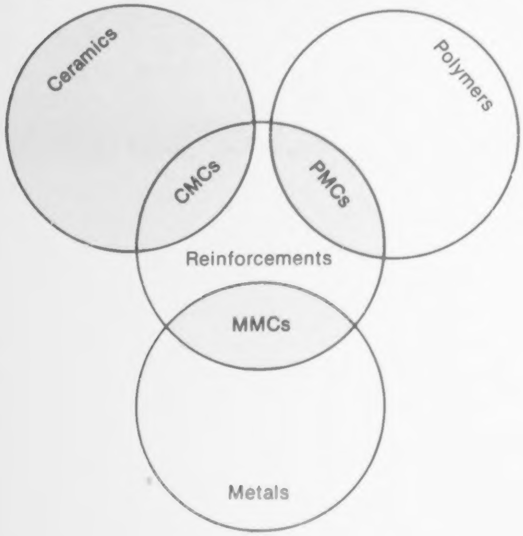
New structural materials can be classified as ceramics, polymers, or metals, as shown in figure 1-1. Two or more of these materials can be combined together to form a composite that has properties superior to those of its constituents. Composites generally consist of fibrous or particulate reinforcements held together by a common matrix, as illustrated in figure 1-2. Continuous fiber reinforcement enhances the structural properties of the composite far more than particles do. However, fiber-reinforced composites are also more expensive and difficult to fabricate.

Composites are classified according to their matrix phase. Thus, there are ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Materials within these categories are often called "advanced" if they exhibit properties, such as high temperature strength or high stiffness per unit weight, that are significantly better than those of more conventional structural materials, such as steel and aluminum. This assessment focuses on advanced structural ceramics (including CMCs), PMCs, and MMCs. New metal alloys and unreinforced engineering plastics, which may also legitimately be considered advanced materials, are not covered.

Figure 1-3 compares the maximum use temperatures of the three primary categories of structural materials. Organic materials such as polymers generally melt or char above 600° F (316° C); the most refractory metals lose their useful strength above 1900° F (1038° C); ceramics, however, can retain their strength above 3000° F (1649° C) and can potentially be useful up to 5000° F (2760° C). In applications such as heat engines and heat exchangers, in which efficiency increases with operating temperature, ceramics offer potential energy savings and cost savings through simpler designs than would be possible with metals.

Figure 1-4 compares the "specific" strength and stiffness (strength and stiffness per unit weight) of some advanced materials with those of conventional metals. The specific stiffness of aluminum can be increased by a factor of 3 by mixing the metal with 50 percent by volume silicon car-

Figure 1-1.—The Family of Structural Materials



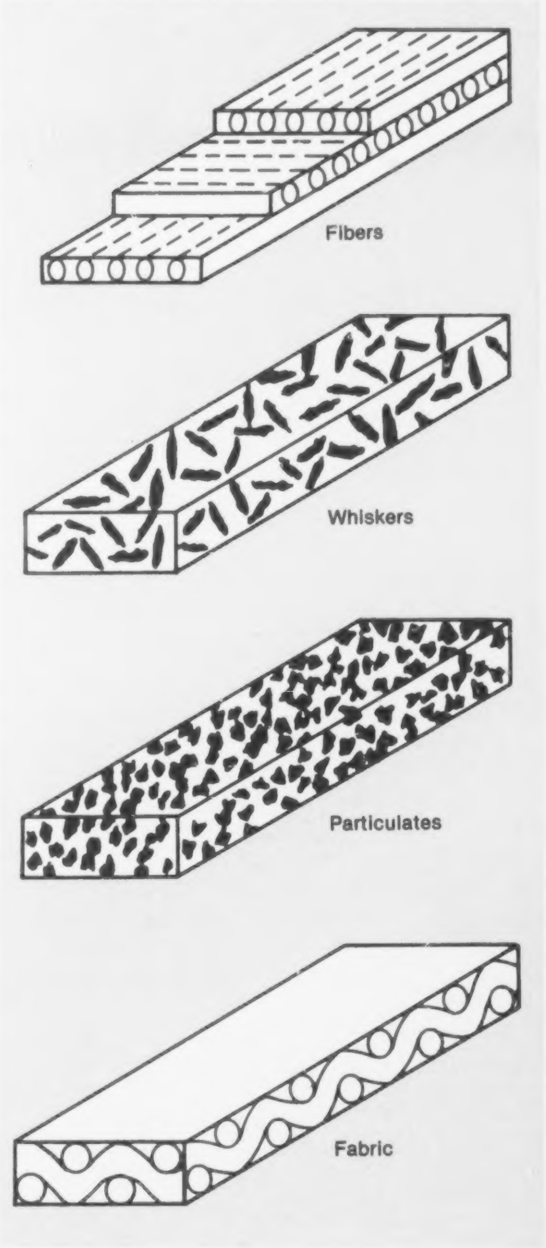
Includes ceramics, polymers, and metals. Reinforcements added to these materials produce ceramic matrix composites (CMCs), polymer matrix composites (PMCs), and metal matrix composites (MMCs). Materials in the shaded regions are discussed in this assessment.

SOURCE: Office of Technology Assessment, 1988.

bide fibers to form an MMC. Even more impressive are PMCs such as graphite fiber-reinforced epoxy (graphite/epoxy), which may have specific strengths and stiffnesses up to 4 times those of steel and titanium (measured along the direction of fiber reinforcement). Such properties make it possible to build composite structures having the same strength and stiffness as metal structures but with up to 50 percent less weight, a major advantage in aircraft and space applications.

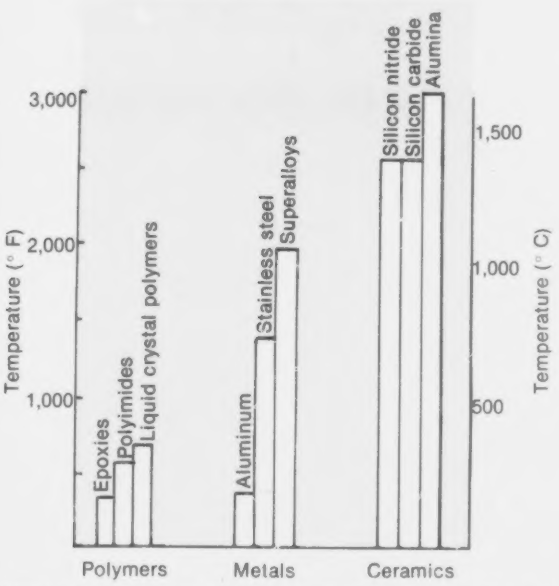
Although the physical and mechanical properties of ceramics and composites are impressive, the true hallmark of these advanced materials is that they are "tailored" materials; that is, they are built up from constituents to have the properties required for a given application. Furthermore, a composite structure can be designed so that it has different properties in different directions or locations. By judicious use of fiber or other reinforcement, strength or stiffness can be enhanced only in those locations where they are most needed. Great efficiencies of design and cost are made possible by this selective placement of the reinforcement.

Figure 1-2.—Composite Reinforcement Types



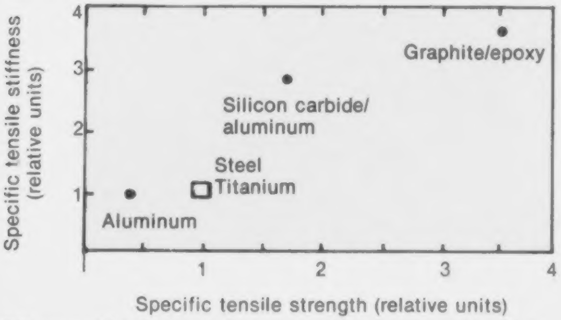
SOURCE: Carl Zweben, General Electric Co.

Figure 1-3.—Maximum Use Temperatures of Various Structural Materials



SOURCE: "Guide to Selecting Engineered Materials," a special issue of *Advanced Materials and Processes*, vol. 2, No. 1, 1987.

Figure 1-4.—Comparison of the Specific Strength and Stiffness of Various Composites and Metals[a]



Silicon carbide fiber-reinforced aluminum and graphite fiber-reinforced epoxy composites exhibit many times the strength and stiffness of conventional metals.

[a] Specific properties are ordinary properties divided by density. Properties are measured along the direction of fiber reinforcement.

[b] Steel: AISI 304; Aluminum: 6061-T6; Titanium: Ti-6Al-4V).

SOURCE: Carl Zwe[illegible], General Electric Co.

The development of advanced materials has opened a whole new approach to engineering design. In the past, the designer has started with a material and has selected discrete manufacturing processes to transform it into the finished structure. With the new tailored materials, the designer starts with the final performance requirements and literally creates the necessary materials and the structure in an integrated manufacturing process. Thus, with tailored materials, the old concepts of materials, design, and fabrication processes are merged together into the new concepts of integrated design and manufacturing.

These technologies differ greatly in their levels of maturity; e.g., PMCs are by far the most developed, whereas CMCs are still in their infancy. In addition, the applications and market opportunities for these materials vary widely. For these reasons, the three primary categories of materials treated in this assessment are discussed separately below.

Ceramics

Ceramics encompass all solids that are neither organic nor metallic. Compared with metals, ceramics have superior wear resistance, high temperature strength, and chemical stability; they also generally have lower thermal conductivity, thermal expansion, and lower toughness (i.e., they tend to be brittle). This brittleness causes them to fail catastrophically when applied stress is sufficient to propagate cracks that originate at microscopic flaws in the material. Flaws as small as 20 micrometers (about one one-thousandth of an inch) can reduce the strength of a ceramic component below useful levels.

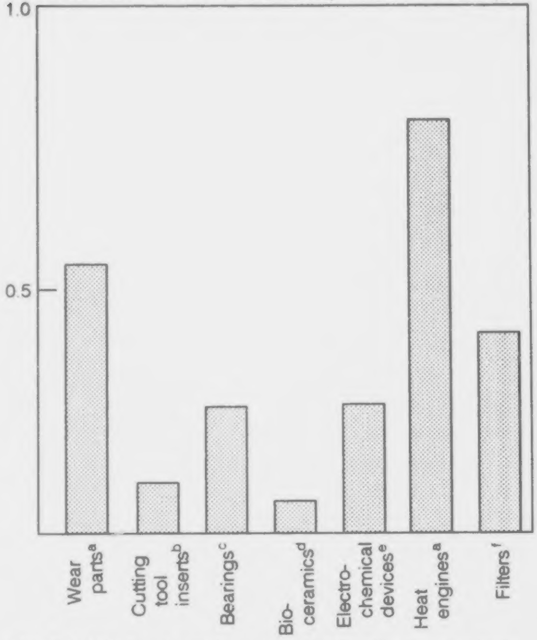
Several approaches have been taken to improve the toughness of ceramics. The most satisfactory is to design the microstructure of the material to resist the propagation of cracks. Ceramic matrix composites, which contain dispersed ceramic particulates, whiskers, or continuous fibers, are an especially promising technology for toughening ceramics. Another approach is the application of a thin ceramic coating to a metal substrate; this yields a component with the surface properties of a ceramic combined with the high toughness of metal in the bulk.

Market Opportunities for Ceramics

Market demand for structural ceramics is not driving their development in most applications at the present time. In 1987, the U.S. market for advanced structural ceramics was estimated at only $171 million, primarily in wear-resistant applications. Projections to the year 2000, though, place the U.S. market between $1 billion and $5 billion annually, spread among many new applications discussed below.

Early estimates that projected a $5 billion U.S. market for ceramics in automotive heat engines (gasoline, diesel, or gas turbine) by the year 2000 now appear to have been too optimistic. More recent estimates indicate that the U.S. ceramic heat engine market in the year 2000 will be less than $1 billion. However, a large number of other commercial applications for ceramics are possible over this time period; examples are given in figure 1-5.

Figure 1-5.—Projected U.S. Markets for Structural Ceramics in the Year 2000 (billions of dollars)



SOURCES: [a] U S Department of Commerce, "A Competitive Assessment of the U S Advanced Ceramics Industry" (Washington, DC, U S Government Printing Office, March 1984)

[b] E P Rothman, J Clark, and H K Bowen, "Ceramic Cutting Tools: A Production Cost Model and an Analysis of Potential Demand," Advanced Ceramic Materials, American Ceramics Society, Vol I, No 4, October, 1986, pp 325-331

[c] *High Technology*, March 1986, p 14

[d] Business Communications Co , Inc , as reported in *Ceramic Industry*, Jan 1988, p 10

[e] David W Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985

[f] Assumes a doubling from 1986 Paul Hurley, "New Filters Can Clean Up in New Markets," High Technology, August 1987

Current Production

Ceramics such as aluminum oxide, silicon nitride, and silicon carbide are in production for wear parts, cutting tool inserts, bearings, and coatings. The market share for ceramics in these applications is generally less than 5 percent, but substantial growth is expected. The U.S. markets for the ceramic components alone could be over $2 billion by the year 2000. R&D funding is currently being provided by industry and is driven by competition in a known market. Current military applications in the United States include radomes, armor, and infrared windows.

Ceramics are also in limited production (in Japan) in discrete engine components such as turbochargers, glow plugs, rocker arms, and precombustion chambers, as well as a number of consumer products.

Near-Term Production

Near-term production (the next 10 to 15 years) is expected in advanced bearings, bioceramics (ceramics used inside the body), construction applications, heat exchangers, electrochemical devices, discrete components in automobile engines, and military applications. Large markets are at stake. The technical feasibility has been demonstrated, but scale-up, cost reduction, and design optimization are required before U.S. industry will invest large sums in the needed research. In the meantime, government funding will be required to supplement industry R&D in order to achieve a production capability competitive with foreign sources.

Far-Term Production

Far-term applications (beyond 15 years) of ceramics will require solution of major technical and economic problems. These include an advanced automotive turbine engine, an advanced ceramic diesel (although ceramics could be used in military versions of these engines at an earlier date), some electrochemical devices, military components, and heat exchangers. A variety of other turbine engines, especially turbines for aircraft propulsion and for utility-scale power generation, should also be categorized as far-term. In general, the risks are perceived by U.S. industry to be too high to justify funding the needed research. Advances in these applications are likely to be driven by government funding.

Polymer Matrix Composites

PMCs consist of high strength short or continuous fibers which are held together by a common organic matrix. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the fiber reinforcement.

PMCs are often divided into two categories: reinforced plastics and so-called "advanced composites." The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no clear-cut line separating the two. Plastics reinforced with relatively low-stiffness glass fibers are inexpensive, and they have been in use for 30 to 40 years in applications such as boat hulls, corrugated sheet, pipe, automotive panels, and sporting goods. Advanced composites, which are used primarily in the aerospace industry, have superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers (e.g., high stiffness glass, graphite, aramid, or other organic fibers). In this assessment, only market opportunities for advanced composites are considered.

Chief among the advantages of PMCs is their light weight coupled with high stiffness and strength along the direction of reinforcement. Other desirable properties include superior resistance to corrosion and fatigue. One generic limitation of PMCs is temperature. An upper limit for service temperatures with present composites is about 600° F (316° C). With additional development, however, temperatures near 800° F (427° C) may be achieved.

Market Opportunities for Polymer Matrix Composites

About 85 percent of PMCs used today are glass fiber-reinforced polyester resins. Currently, less than 2 percent of PMCs are advanced composites such as those used in aircraft and aerospace applications. However, U.S. production of advanced PMCs is projected to grow by 15 percent annually for the remainder of the century, increasing from a 1985 value of $1.4 billion to nearly $12 billion by the year 2000. The industry continues to be driven by aerospace markets, with defense applications projected to grow by as much as 22 percent annually in the next few years.

Current Production

Aerospace applications of polymer composites account for about 50 percent of current PMC sales in the United States. Sporting goods, such as golf clubs and tennis rackets, account for 25 percent. The PMC sporting goods market is considered mature, however, with projected annual growth rates of only 3 percent. Automobiles and industrial equipment round out the current list of major uses of advanced composites, with a 25 percent share.

Near-Term Production

Advanced PMCs were introduced into the horizontal stabilizer of the F-14 fighter in 1970, and they have since become the baseline materials in high-performance fighter and attack aircraft. The major near-term challenge for composites will be use in large military and commercial transport aircraft. Advanced PMCs currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757, but that fraction could eventually rise to more than 65 percent in new transport designs.

The single largest near-term opportunity for PMCs is in the manufacture of automobiles. Composites currently are in limited production in body panels, drive shafts, and leaf springs. By the late 1990s, composite automobile bodies could be introduced by Detroit in limited production. The principal advantage of a composite body would be the potential for parts consolidation, which could result in lower assembly costs. Composites can also accommodate styling changes with lower retooling costs than would be possible with metals.

Additional near-term markets for polymer composites include medical implants, reciprocating industrial machinery, storage and transportation of corrosive chemicals, and military vehicles and weapons.

Far-Term Production

Beyond the turn of the century, PMCs could be used extensively in construction applications such as bridges, buildings, manufactured housing, and marine structures where salt water corrosion is a problem. Realization of this potential will depend on development of cheaper materials, changes in building codes, and of designs that take advantage of compounding benefits of PMCs, such as reduced weight and increased durability. In space, a variety of composites will be used in the proposed National Aerospace Plane, and they are also being considered for the tubular frame of the National Aeronautics and Space Administration's (NASA) space station. Composites of all kinds, including MMCs, PMCs, and CMCs would be a central feature of space-based weapons systems, such as those under consideration for ballistic missile defense.

Metal Matrix Composites

MMCs usually consist of a low-density metal such as aluminum or magnesium reinforced with particulates or fibers of a ceramic material, such as silicon carbide or graphite. Compared with the unreinforced metal, MMCs have significantly greater stiffness and strength, as indicated in figure 1-4; however, these properties are obtained at the cost of lower ductility and toughness.

Market Opportunities for Metal Matrix Composites

At present, metal matrix composites remain primarily materials of military interest in the United States, because only the Department of Defense's (DoD) high-performance specifications have justified the materials' high costs. The future commercial markets for MMCs remain uncertain for two reasons. First, their physical and mechanical properties rarely exceed those of PMCs or CMCs. For example, the melting point of the metal matrix keeps the maximum operating temperature for MMC components to a level significantly below that of ceramics; as new high-temperature PMCs are developed, this squeezes further the temperature window in which MMCs have an advantage. Also, because the density of the metal matrix is higher than that of a polymer matrix, the strength-to-weight ratio of MMCs is generally less than that of PMCs (figure 1-4).

A second source of uncertainty relates to cost. MMCs tend to cluster around two extreme types: one type consists of high-performance composites reinforced with expensive continuous fibers and requiring expensive processing methods; the other consists of relatively low-cost, low-performance composites reinforced with relatively inexpensive particulates and fibers. The cost of the first type is too high for any but military or space applications, whereas the cost/benefit advantages of the second type over metal alloys remain in doubt.

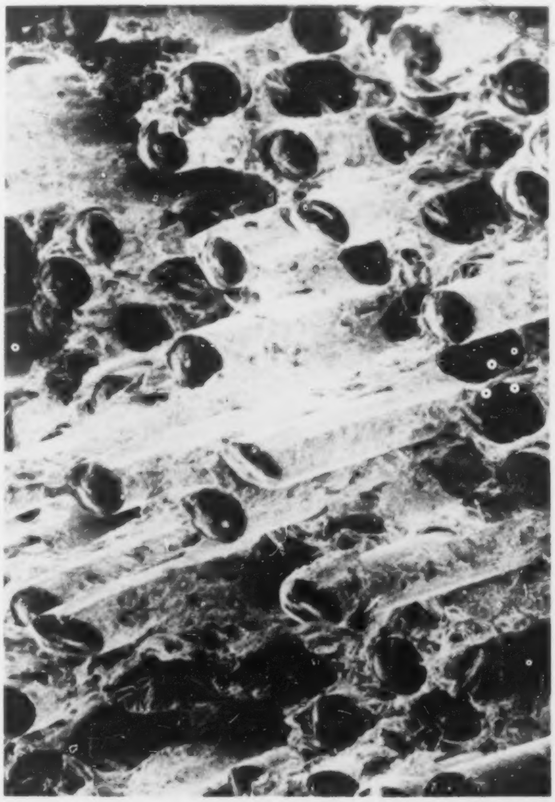


Photo credit: United Technologies Research Center

Fracture surface of boron fiber-reinforced aluminum metal matrix composite.

Thus, it is unclear whether MMCs will become the materials of choice for a wide variety of applications or whether they will be confined to specialty niches in which the combinations of properties required cannot be satisfied by other materials. The key factors will be whether the costs of the reinforcements and of the manufacturing processes can be reduced while the properties are improved. Costs could be reduced substantially if net-shape processes currently used with metals, such as casting or powder techniques, can be successfully adapted to MMCs.

Current Production

Current markets for MMCs are primarily in military and aerospace applications. Experimental MMC components have been developed for use in aircraft, jet engines, missiles, and the NASA space shuttle. The first production application of a particulate-reinforced MMC is a set of covers for a missile guidance system.

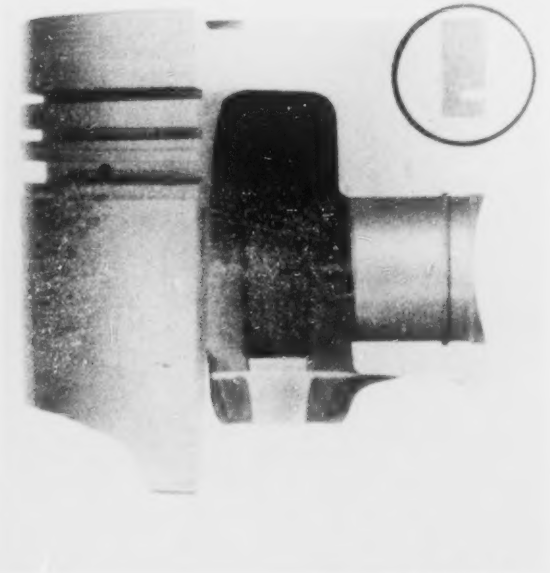


Photo credit: Toyota Motor Corp.

Aluminum diesel engine piston with local fiber reinforcement in ring groove area.

The most significant commercial application of MMCs to date is an aluminum diesel engine piston produced by Toyota that is locally reinforced with ceramic fibers. Toyota produces about 300,000 annually. The ceramic reinforcement provides superior wear resistance in the ring groove area. Although data on the production costs of these pistons are not available, this development is significant because it suggests that MMC components can be reliably mass-produced to be competitive in a very cost-sensitive application.

Future Production

Based on information now in the public domain, the following military and aerospace applications for MMCs appear attractive: high-temperature fighter aircraft engines and structures; the National Aerospace Plane skin and engines; high-temperature missile structures; high-speed mechanical systems, and electronic packaging.

Applications that could become commercial in the next 5 to 15 years include automotive pistons, brake components, connecting rods, and rocker arms; rotating machinery, such as propeller shafts and robot components; computer equipment, prosthetics, electronic packaging, and sporting goods. However, the current level of development effort appears to be insufficient to bring about commercialization of any of these applications in the United States in the next 5 years, with the possible exception of diesel engine pistons.

MMC materials with high specific stiffness and strength could be used in applications in which an important factor is reducing weight. Included in this category are land-based vehicles, aircraft, ships, and high-speed machinery. The relatively high cost of MMCs will probably prevent their extensive use in commercial land-based vehicles and ship structures. However, they may well be used in specific mechanical components such as propeller shafts, bearings, pumps, transmission housings and components, gears, springs, and suspensions.

Research and Development Priorities

In spite of the fact that ceramics, PMCs, and MMCs are at different stages of technological maturity, the R&D challenges for all three categories are remarkably similar. The four most important R&D priorities are given below.

Processing Science

This is the key to understanding how processing variables such as temperature, pressure, and composition influence the desired final properties. The two principal goals of processing science should be to support development of new, low-cost manufacturing methods, and to help bring about better control over reproducibility so that large numbers of components can be manufactured within specification limits.

Structure-Property Relationships

The tailorable properties of advanced materials offer new opportunities for the designer. However, because advanced materials and structures are more complex than metals, the relationships among the internal structure, mechanical properties, and failure mechanisms are less well understood. A better understanding of the effects of an accumulation of dispersed damages on the failure mechanisms of composites is especially desirable.

Behavior in Severe Environments

Many applications may require new materials to withstand high-temperature, corrosive, or erosive environments. These environments may exacerbate existing flaws or introduce new flaws, leading to failure. Progress in this area would facilitate reliable design and life prediction.

Matrix-Reinforcement Interface in Composites

The poorly understood interfacial region has a critical influence on composite behavior. Particularly important would be the development of interfacial coatings that would permit the use of a single fiber with a variety of matrices.

FACTORS AFFECTING THE USE OF ADVANCED MATERIALS

Broader use of advanced structural materials will require not only solutions to technical problems, but also changes in attitudes among researchers and end users who are accustomed to thinking in concepts more appropriate to conventional materials.

Traditionally, materials are considered to be one (usually inexpensive) input in a long chain of discrete design and manufacturing steps that result in the output of a product. The new tailored materials require a new paradigm. The materials and the end products made from them become indistinguishable, joined by an integrated design and manufacturing process. This necessitates a closer relationship among researchers, designers, and production personnel, as well as new approaches to the concept of materials costs.

Integrated Design and Manufacturing

Advanced ceramics and composites should really be considered as structures rather than as materials. Accordingly, it becomes essential to have a design process capable of producing highly integrated and multifunctional structures. Consider the body structure of an automobile. A metal body currently has between 250 and 350 distinct parts. Using PMCs, this number could be reduced to between 2 and 10.

Because composites can be tailored in so many ways to the various requirements of a particular engineering component, the key to optimizing cost and performance is a fully integrated design process capable of balancing all of the relevant design and manufacturing variables. Such a design process requires an extensive database on matrix and fiber properties, sophisticated software capable of modeling fabrication processes, and three-dimensional analysis of the properties and behavior of the resulting structure. Perhaps the most important element in the development of integrated design algorithms will be an understanding of the relationships among the constituent properties, microstructure, and the macroscopic properties of the structure. The R&D priorities listed above are intended to provide this information.

Automation

The need for integrated design and manufacturing sheds light on the extent to which automation will be able to reduce the costs of advanced materials and structures. Automation can be used for many purposes in advanced materials manufacturing, including design, numerical modeling, materials handling, process controls, assembly, and finishing. Automation technologies that aid in integrating design and manufacturing will be helpful. For example, computer-aided design (CAD) and numerical modeling are likely to help bring the designer and production engineer in closer contact.

Automation in the form of computer control of advanced materials processing equipment is an important evolving technology for solving current manufacturing problems. In ceramics, new processes controlled by microprocessors or computers will be critical in minimizing flaw populations and increasing process yields. In PMCs, the costly process of hand lay-up will be replaced by computer-controlled tape laying machines and filament winding systems. However, large-scale process automation will be effective in reducing costs only if the process is well characterized and the allowable limits for processing variables are well understood. In general, manufacturing processes for advanced materials are still evolving, and attempts to automate them in the near term could be premature.

Multidisciplinary Approach

Advanced materials development lends itself naturally to—and probably will demand—relaxing the rigid disciplinary boundaries among different fields. This is true whether the materials development is performed in government laboratories, universities, or industry. For example, the necessity for integrating design and manufacturing of advanced materials and structures implies closer working relationships among industry professionals involved in manufacturing a product. For a typical ceramic component, an industry team could include one or more professionals from each of the disciplines in table 1-2.

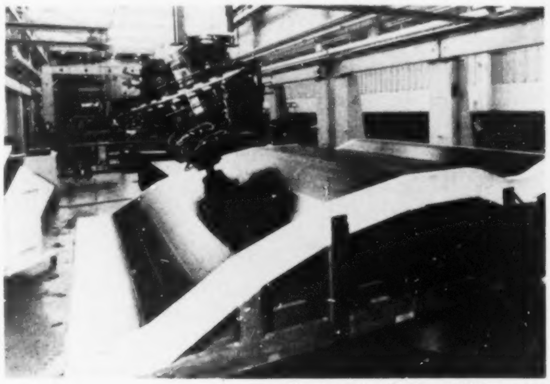


Photo credit: Cincinnati Milacron Co.

Composite tape-laying machine shown applying 3-inch-wide tape to compound-angle "tool" in the manufacture of an aircraft part.

Education and Training

The expanding market opportunities for ceramics and composites will require more scientists and engineers with broad backgrounds in these fields. At present, only a few universities offer comprehensive courses in ceramic or composite materials. There is also a shortage of prop-

Table 1-2.—Hypothetical Multidisciplinary Design Team for a Ceramic Component

Specialist	Contribution
Systems engineer	Defines performance
Designer	Develops structural concepts
Stress analyst	Determines stress for local environments and difficult shapes
Metallurgist	Correlates design with metallic properties and environments
Ceramist	Identifies proper composition, reactions, and behavior for design
Characterization analyst	Utilizes electron microscopy, X-ray, fracture analysis, etc. to characterize material
Ceramic manufacturer	Defines production feasibility and costs

SOURCE: J.J. Mecholsky, "Engineering Research Needs of Advanced Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

erly trained faculty members to teach such courses. The job market for graduates with advanced degrees in ceramic or composite engineering is good, and can be expected to expand in the future. Stronger relationships between industry and university laboratories are providing greater educational and job opportunities for students.

There is a great need for continuing education and training opportunities for designers and engineers in industry who are unfamiliar with the new materials. In the field of PMCs, for instance, most of the design expertise is concentrated in the aerospace industry. Small businesses, professional societies, universities, and Federal laboratories could all play a role in providing this training. Continuing education regarding the potential of advanced materials is particularly important in relatively low-technology industries such as construction, which must purchase, rather than develop, the materials they use.

Beyond the training of professionals, there is a need for the creation of awareness of advanced materials technologies among corporate executives, planners, technical media personnel, and the general public. In recent years, the number of newspaper and magazine articles about the remarkable properties of ceramics and composites has increased, as has the number of technical journals associated with these materials. The success of composite sports equipment, including skis and tennis rackets, shows that such materials can have a high-tech appeal to the public, even if they are relatively expensive.

Systems Approach to Costs

Without question, the high cost per pound of advanced materials will have to come down before they will be widely used in high-volume, low-cost applications. This high cost is largely attributable to the immaturity of the fabrication technology and to low production volumes, and can be expected to drop significantly in the future. For example, a pound of standard high-strength carbon fiber used to cost $300, but now costs less than $20, and new processes based on synthesis from petroleum pitch promise to reduce the cost even further. However, these advanced materials will always be more expensive than basic metals. Therefore, end users must take advantage of potential savings in fabrication, installation, and life-cycle costs to offset the higher material costs; in other words, a systems approach to costs is required.

As the example of the PMC automobile body cited above demonstrates, savings in tooling, assembly, and maintenance costs could result in lower cost, longer lasting cars in the future. Viewed from this systems perspective, advanced materials may become more cost-effective than conventional materials in many applications.

Energy Costs

The cost of energy used in the manufacture of advanced materials and structures is generally only 1 to 2 percent of the cost of the finished product. However, the energy cost savings obtained over the service life of the product is a major potential advantage of using the new materials. For example, the high temperature capabilities of ceramics can be used to increase the thermal efficiency of heat engines, heat exchangers, and furnace recuperators. Fuel savings also result from reducing the weight of ground vehicles and aircraft through the use of lightweight composites.

The decline of fuel prices in recent years has reduced energy cost savings as a selling point for new products, and has therefore reduced the attractiveness of new materials. For example, in the early 1980s one pound of weight saved in a commercial transport aircraft was worth $300 in fuel savings over the life of the aircraft, but is now worth less than $100. At $300 per pound of weight saved, the higher cost of using composites could be justified; at a premium of only $100 per pound, aluminum or aluminum-lithium alloys are more attractive. Persistently low fuel prices would delay the introduction of advanced materials into such applications.

IMPACTS OF ADVANCED MATERIALS ON MANUFACTURING

The advent of advanced structural materials raises questions concerning their impact on existing manufacturing industries in the United States. This impact can be conceptually divided into two categories: substitution by direct replacement of metal components in existing products, and use in new products that are made possible by the new materials. Compared with other supply and demand factors affecting basic metals manufacturing, the impact of direct substitution of advanced materials for these metals is likely to be relatively minor. In contrast, more innovative application of the materials to new or redesigned products could have substantial impact on manufacturing industries, including development of more competitive products, and new industries and employment opportunities, as described below.

Substitution

From the viewpoint of the commercial end user considering the introduction of a new material into an existing product, the material must perform at least as well as the existing material, and do so at a lower cost. This cost is generally calculated on the basis of direct substitution of the new material for the old material in a particular component, without redesign or modification of surrounding components. In fact, if substantial redesign is necessary, this is likely to be considered a significant disincentive for the substitution.

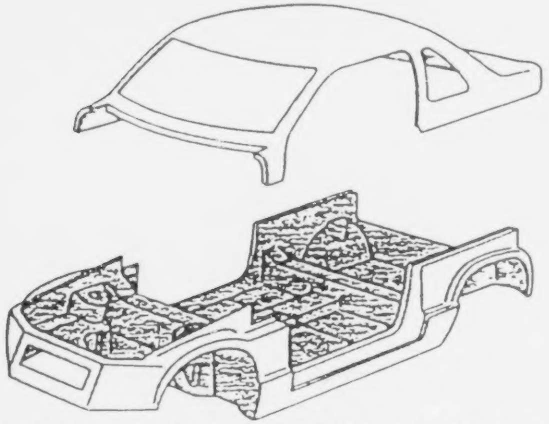
Generally, advanced materials cannot compete with conventional materials on a dollars-per-pound substitution basis. Direct substitution of a ceramic or composite part for a metal part does not exploit the superior properties and design flexibility inherent in advanced materials, key advantages which can offset their higher cost. Yet direct substitution is frequently the only option considered by end users, who are wary of making too many changes at once. This Catch-22 situation is a major barrier to the use of advanced materials in large volume applications. However, commercial end users who wish to exploit the long-term opportunities offered by advanced materials may fail to achieve their goal unless they are willing to employ advanced materials more aggressively in the near term, thereby gaining production experience.

It is sometimes suggested that substitution of advanced materials for steel and aluminum will soon become a significant factor affecting the demand for these metals. OTA's analysis indicates that this is highly unlikely. Because of their low cost and manufacturability, these metals are ideally suited for many of the applications in which they are now used, and will not be replaced by advanced materials. Moreover, the threat of substitution has led to the development of new alloys with improved properties, such as high-strength, low-alloy steel and aluminum-lithium. The availability of these and other new alloys will make it even more difficult for new, nonmetallic materials to substitute for metals. As new materials technologies mature and costs come down, significant displacement of metals could occur in four markets: aircraft, automobiles, containers, and construction. However, in those applications where substitution is substantial, by far the greatest volume of steel and aluminum will be displaced by relatively low-performance, low-cost materials, such as unreinforced plastics, sheet molding compounds, and high-strength concrete.

Innovative Designs and New Products

The automotive industry provides an excellent paradigm for understanding the potential impact of using advanced materials in cost-sensitive manufacturing applications. Design teams at the major automakers are currently evaluating the use of PMCs in primary body structures and chassis/suspension systems, as illustrated in figure 1-6. The potential advantages of using PMCs include: weight reduction and resulting fuel economy; improved overall quality and consistency in manufacturing; lower assembly costs due to parts consolidation; improved ride performance; product differentiation at a reduced cost; lower investment costs for plant, facilities, and tooling; improved corrosion resistance; and lower operating costs. These advantages reflect a systems

Figure 1-6.—Typical Body Construction Assembly Using Two Major PMC Moldings



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries: Case Study: Composite Automobile Structure," contractor report for OTA, March 1987.

approach to costs, as described above. However, major challenges remain that will require extensive R&D to resolve. These include: lack of high-speed, high-quality, low-cost manufacturing processes; uncertainties regarding performance requirements, particularly crash integrity and long-term durability; lack of adequate technologies for repair and recycling of PMC structures; and uncertain customer acceptance.

There is a growing body of evidence that glass fiber-reinforced composites are capable of meeting the functional requirements of the most highly loaded automotive structures. However, major innovations in fabrication technologies are still required. There are several candidate fabrication methods, including resin transfer molding, compression molding, and filament winding. At this time, none of these methods can satisfy all of the production requirements; however, resin transfer molding seems the most promising.

Large-scale adoption of PMC automotive structures would have a major impact on the fabrication and assembly of automobiles. For instance, metal forming presses would be replaced by a much smaller number of molding units, the current large number of welding machines would be replaced by a limited number of adhesive bonding fixtures, and the assembly sequence would be modified to reflect the tremendous reduction in parts. Factories would be smaller because fewer assembly machines require less floor space.

The overall labor content of producing a PMC automobile body would be reduced as numerous operations would be eliminated. However, it is important to note that body assembly is not a labor-intensive segment of total assembly. Other assembly operations that are more labor-intensive (e.g., trim) would not be significantly affected. Thus, the overall decreases in direct labor due to adoption of PMCs may be relatively small. The kinds of skills required of factory personnel would be somewhat different, and significant retraining would be necessary. However, the overall skill levels required are likely to be similar to those in use today.

Extensive use of PMCs by the automotive industry would cause completely new industries to arise, including a comprehensive network of PMC repair facilities, molding and adhesive bonding equipment suppliers, and a recycling industry based on new technologies. Current steel vehicle recycling techniques will not be applicable to PMCs, and cost-effective recycling technologies for PMCs have yet to be developed. Without the development of new recycling methods, incineration could become the main disposal process for PMC structures. The lack of acceptable recycling and disposal technologies could translate into higher costs for PMC structures relative to metals.

INDUSTRY INVESTMENT CRITERIA FOR ADVANCED MATERIALS

The potential for advanced materials in the manufacturing sector will not be realized unless companies perceive that their criteria for investment in R&D and production will be met. The investment criteria used by advanced materials companies vary depending on whether they are materials suppliers or users; whether the intended markets are military or commercial; and whether the end use emphasizes high materials performance or low cost.

Suppliers of advanced structural materials tend to be technology-driven; they are focused primarily on the superior technical performance of advanced materials and are looking for both military and commercial applications. Suppliers tend to take a long-term view, basing investment decisions on qualitative assessments of the technical potential of advanced materials. On the other hand, users of advanced materials tend to be market-driven; they are focused primarily on short-term market requirements, such as return on investment and time to market.

Frequently, advanced materials suppliers and users operate in both military and commercial markets. However, the investment criteria employed in the two cases are very different. Defense contractors are able to take a longer term perspective because they are able to charge much of their capital equipment to the government, and because the defense market for the materials and structures is well-defined. Commercial end users, on the other hand, must bear the full costs of their production investments, and face uncertain returns. Their outlook is therefore necessarily shorter term. This difference in market perspective has hampered the transfer of technology from advanced materials suppliers (who frequently depend on defense contracts to stay in business) to commercial users, and it underlines the importance of well-defined markets as a motivating force for industry investments in advanced materials.

Cost and Performance

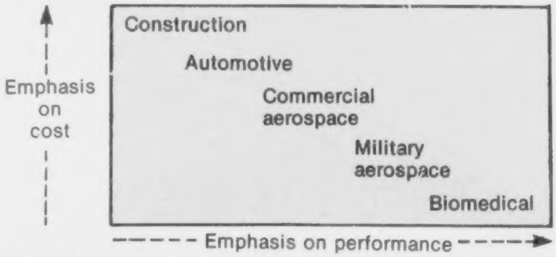
The many applications of advanced structural materials do not all have the same cost and performance requirements. Accordingly, the investment criteria of user companies specializing in different product areas are different. In general, barriers to investment are highest in cost-sensitive areas such as construction and automobiles, wherein expensive new materials must compete with cheap, well-established conventional materials. Barriers are lowest for applications in which a high materials cost is justified by superior performance, such as medical implants and aircraft.

Figure 1-7 provides a schematic view of the relative importance placed on high materials performance versus cost in a spectrum of industrial end uses. In commercial aircraft, automotive, and construction markets, acquisition costs and operating expenses are the major purchase criteria, with progressively less emphasis on high material performance. In military aerospace and biomedical markets, functional capabilities and performance characteristics are the primary purchase criteria.

Because advanced materials may cost as much as 100 times more on a per-pound basis than metals such as steel and aluminum, their first use has generally been in the less cost-sensitive end uses of figure 1-7, particularly in the military. However, because military production runs are typically small, there is little incentive to develop low-cost, mass production manufacturing processes that would make the materials more attractive for commercial applications such as automobiles. The lack of such processes is a major barrier preventing more widespread commercial use of advanced structural materials. This suggests that greater emphasis on military R&D programs to develop low-cost fabrication techniques could facilitate the diffusion of military materials technology into the commercial sector.

The major potential sales value of advanced materials lies in the commercial industries in the middle of figure 1-7; i.e., in aircraft, automobiles, industrial machinery, etc. This is because construction materials are used in high volume but must have a very low cost, and military and biomedical materials can have high allowable costs,

Figure 1-7.—Relative Importance of Cost and Performance in Advanced Materials User Industries



Barriers to the use of advanced materials decrease from upper left to lower right.

SOURCE: Technology Management Associates, "Industrial Criteria for Investment Decisions in R&D and Production Facilities," contractor report for OTA, January 1987.

but are used in relatively low volume. However, end users in these "middle" industries do not perceive that use of the new materials will be profitable within the next 5 years, the planning horizon of most companies. Thus, there is virtually no market pull on these technologies in the United States. This suggests that an important policy tool for accelerating the commercialization of advanced materials is to increase incentives for investment by commercial end users.

INTERNATIONAL BUSINESS TRENDS

Advanced structural materials industries have become markedly more international in character in the past several years. In collaboration with industry, governments around the world are investing large sums in multi-year programs to facilitate commercial development. Through acquisitions, joint ventures, and licensing agreements, the firms involved have become increasingly multinational, and are thereby able to obtain access to growing markets and achieve lower production costs. Critical technological advances continue to be made outside the United States; e.g., the carbon fiber technology developed in Great Britain and Japan, and hot isostatic pressing technology developed in Sweden.

This trend toward internationalization of advanced structural materials technologies has many important consequences for government and industry policymakers in the United States. They can no longer assume that the United States will dominate the technologies and the resultant applications. The flow of technology coming into the United States from abroad may soon be just as significant as that flowing out. Moreover, the increasingly multinational character of materials industries suggests that the rate of technology flow among firms and countries is likely to increase. The United States will not be able to rely on a superior R&D capability to provide an advantage in developing commercial products. Furthermore, if there is no existing infrastructure in the United States for quickly appropriating the R&D results for economic development, the results will quickly be used elsewhere.

Ceramics

The value of advanced ceramics consumed in the United States, and produced in Japan and Western Europe in 1985 are estimated in table 1-3. (U.S. production data were not available.) In each geographic region, electronic applications, such as capacitors, substrates, and integrated circuit packages, accounted for over 80 percent of the total. Structural applications, including wear parts and cutting tool inserts, accounted for the remainder.

By a margin of nearly 2 to 1, the U.S. ceramics companies interviewed by OTA felt that Japan is the world leader in advanced ceramics R&D. Without question, Japan has been the leader in actually producing advanced ceramic products for both industrial and consumer use. Japanese end users exhibit a commitment to the use of these materials not found in the United States. This commitment is reflected in the fact that although the U.S. and Japanese Governments spend comparable amounts on ceramics R&D (roughly $100 to $125 million in fiscal year 1985, see table 1-4), estimated spending by Japanese industry is about four times that of its government, while in the United States, industry investment in advanced ceramics R&D (estimated at $153 million in fiscal year 1986) is only slightly higher than government spending. Ceramics technology has a high profile in Japan, due in part to production of advanced ceramic consumer goods, such as fish hooks, pliers, scissors, and ballpoint pen tips.

Table 1-3.—Estimated Production Value of Advanced Ceramics, 1985 (millions of dollars)

Region	Electronic applications	Structural applications	Total
Japan	1,920	360	2,280
United States[a]	1,763	112	1,875
Western Europe	390	80	470

[a] Consumption in 1985, according to Business Communications Co., Inc., Norwalk, CT.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

Table 1-4.—Estimated Government Funding in Several Countries for Advanced Ceramics R&D in 1985[a] (millions of dollars)[b]

United States	$125
Japan	100
West Germany	75
France	64
United Kingdom	51
Sweden	7
Italy	6
Finland	5
The Netherlands	4
Belgium	1.5
Other[c]	3

[a] Includes funding for electronic and structural applications.

[b] Includes government funding for materials, office expenses (e.g., salaries), and facilities in research centers, universities, and private industry.

[c] Includes Denmark, Ireland, Norway, and Switzerland.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

Japanese ceramics companies are far more vertically and horizontally integrated than U.S. companies, a fact that probably enhances their ability to produce higher quality ceramic parts at lower prices. However, these companies are still losing money on the structural ceramic parts they produce. This reflects the long-term view of Japanese companies regarding the future of ceramics technologies.

The Japanese market for advanced structural ceramics is likely to develop before the U.S. market. However, given the self-sufficiency of the Japanese ceramics industry, this market is likely to be difficult to penetrate by U.S. suppliers. In contrast, Japanese ceramics firms, which already dominate the world market for electronic ceramics, are strongly positioned to exploit the U.S. structural ceramics market as it develops. One such firm, Kyocera, the largest and most highly integrated ceramics firm in the world, has already established subsidiaries and, recently, an R&D center in the United States.

West Germany, France, and the United Kingdom all have initiated substantial programs in advanced ceramics R&D, as indicated in table 1-4. West German companies have a strong position in powders and finished products, whereas France has developed a strong capability in CMCs. Meanwhile, the European Community (EC) has earmarked about $220 million for R&D on advanced materials (including ceramics) between 1987 and 1991. Overall, industry investment in advanced ceramics in Western Europe is thought to be roughly in the same proportion to government spending as in the United States, i.e., far less than in Japan. Western Europe appears to have all of the necessary ingredients for developing its own structural ceramics industry.

Polymer Matrix Composites

The value of advanced PMC components produced in the United States, Western Europe, and Japan in 1985 was $2.1 billion, divided roughly as follows: the United States, $1.3 billion; Western Europe, $600 million; and Japan, $200 million. As shown in table 1-5, the U.S. and European markets are dominated by aerospace applications. In the United States, PMC development is being driven by military and space programs, whereas in Western Europe development is being keyed more heavily to commercial aircraft use. In contrast, the Japanese market is dominated by sporting goods applications.

On the strength of its military aircraft and aerospace programs, the United States leads the world in advanced PMC technology. Due to the attractiveness of PMCs for new weapons programs, the military fraction of the market is likely to increase in the near term. However, this military technology leadership will not necessarily be translated into a strong domestic commercial industry. Due to the high cost of such military materials and structures, they find relatively little use in commercial applications.

Commercialization of advanced PMCs is an area in which the United States remains vulnerable to competition from abroad. U.S. suppliers

Table 1-5.—Breakdown of Regional Markets for Advanced Composites by End Use

	End use (percentage)[a]		
Region	Aerospace	Industrial[b]	Recreational
United States	50	25	25
Western Europe	56	26	18
Japan	10	35	55

[a] Based on the value of fabricated components.

[b] Includes automotive, medical, construction, and non-aerospace military applications.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

of PMC materials report that foreign commercial end users (particularly those outside the aerospace industry) are more active in experimenting with the new materials than are U.S. commercial end users. For example, Europe is considered to lead the world in composite medical devices. It should be noted, however, that the regulatory environment controlling the use of new materials in the human body is currently less restrictive in Europe than in the United States.

France is by far the dominant force in PMCs in Western Europe, producing more than all other European countries combined, as shown in table 1-6. The United Kingdom, West Germany, and Italy make up the balance. The commercial aircraft manufacturer Airbus Industrie, a consortium of European companies, is the single largest consumer of PMCs. At the European Community level, significant expenditures are being made to facilitate the introduction of PMCs into commercial applications through the BRITE and EURAM programs. In addition, the EUREKA program called Carmat 2000 has proposed to spend $60 million over 4 years to develop PMC automobile structures.

In the past few years, the participation of Western European companies in the U.S. PMC market has increased dramatically. This has occurred primarily through their acquisitions of U.S. companies. One result is that they now control 25 percent of resins, 20 percent of carbon fibers, and 50 percent of prepreg (fibers pre-impregnated with polymer resin, the starting point for many fabrication processes) sales in the United States. These acquisitions appear to reflect their desire to participate more directly in the U.S. defense market and to establish a diversified, worldwide business. A secondary benefit for the European companies is likely to be a transfer of U.S. PMC technology to Europe such that in the future, Europe will be less dependent on the United States for this technology.

Table 1-6.—Distribution of Advanced PMC Business in Western Europe, 1986

Country	Percent of total
France	55%
United Kingdom	15
West Germany	10
Italy	10
All other	10
Total	100%

SOURCE: Strategic Analysis Inc., "Strategies of Suppliers and Users of Advanced Materials," contractor report for OTA, March 1987.

Although Japan is the world's largest producer of carbon fiber, a key ingredient in advanced composites, it has been only a minor participant to date in the advanced composites business. One reason for this is that Japan has not developed a domestic aircraft industry, the sector that currently uses the largest quantities of advanced composites. Another reason is that Japanese companies have been limited by licensing agreements from participating directly in the U.S. market.

Few observers of the composites industry expect this situation to continue. Change could come from at least two directions. First, Japanese fiber producers could abrogate existing agreements and sell their product directly in the U.S. market. Second, based on technology gained through their increasing involvement in joint ventures with Boeing, Japan could launch its own commercial aircraft industry.

Metal Matrix Composites

The principal markets for MMC materials in the United States and Western Europe are in the defense and aerospace sectors. Accordingly, over 90 percent of the U.S. funding for MMC R&D between 1979 and 1986 came from DoD. The structures of the U.S. and European MMC industries are similar, with small, undercapitalized firms supplying the formulated MMC materials. Currently, the matrix is supplied by the large aluminum companies, which are considering forward integration into composite materials. There are also in-house efforts at the major aircraft companies to develop new composites and new processing methods. Many analysts feel that the integration of the MMC suppliers into larger concerns having access to more capital and R&D resources will be a critical step in producing reliable, low-cost MMCs that could be used in large-volume commercial applications.

A potential barrier to the commercial use of MMCs in the United States arises from restrictions imposed on the flow of information about MMCs for national security reasons. Because MMCs are classified as a technology of key military importance, exchanges of technical data on MMCs are severely restricted in the United States and exports of data and material are closely controlled.

Unlike the situation in the United States and Western Europe, the companies involved in manufacturing MMCs in Japan are largely the same as those involved in suppiying PMCs and ceramics; i.e., the large, integrated materials companies. Another difference is that the Japanese MMC suppliers focus primarily on commercial applications, including electronics, automobiles, and aircraft and aerospace. One noteworthy Japanese development is Toyota's introduction of an MMC diesel engine piston consisting of aluminum locally reinforced with ceramic fibers. This is an important harbinger of the use of MMCs in low-cost, high-volume applications, and it has stirred considerable worldwide interest among potential commercial users of MMCs.

GOVERNMENT/UNIVERSITY/INDUSTRY COLLABORATION AND INDUSTRIAL COMPETITIVENESS

Through the years, the United States has built up a strong materials science base in its universities and Federal laboratories. Many observers believe that U.S. industry, universities, and Federal laboratories need to work together more effectively to translate this research base into competitive commercial products. Collaborative programs offer a number of potential contributions to U.S. industrial competitiveness, including an excellent environment for training students, an opportunity to leverage stakeholder R&D investments, and research results that could lead to new products.

Since the early 1980s, numerous collaborative R&D centers have been initiated. These centers follow a variety of institutional models, including industry consortia, university-based consortia such as the National Science Foundation's Engineering Research Centers, quasi-independent institutes (often funded by State government sources), and Federal laboratory/industry programs.

In advanced materials technologies, most current collaborative programs are based at universities or Federal laboratories. OTA's survey of a sample of these programs suggests that such programs are more successful in training students and leveraging R&D investments than they are in stimulating commercial outcomes.

The collaborative research programs and their industrial participants surveyed by OTA do not rank commercialization as a high priority, and they do not systematically track commercial outcomes. Many of the university-based programs concentrate on publishable research and graduate training. Those programs based at Federal facilities are only now beginning to move away from their primary agency missions toward a broader concern with U.S. industrial competitiveness. Generally, industrial participants value their access to skilled research personnel and graduate students more highly than the actual research results generated by the collaboration. This strongly suggests that such collaborative programs should not be viewed as engines of commercialization and jobs, but rather as a form of infrastructure support, providing industry with access to new ideas and trained personnel.

Industrial participants often have only a modest amount of involvement in the planning and operation of the collaborative programs. For the most part, they approach their relationship with research organizations as being a "window to the future." Furthermore, "collaboration" may be an inaccurate description of many of the programs. In large measure, the programs studied by OTA did not involve intense, bench-level interaction between institutional and industrial scientists; rather, the nature of the collaboration seemed to be mostly symbolic.

There are exceptions to these general observations in some of the newer "hybrid" initiatives, which combine both generic and proprietary research in the same program. Often undertaken in conjunction with State government funding, these hybrid organizations seem to incorporate a greater commitment to commercialization and economic development as their mission.

For the results of collaborative research to be commercialized, there must be a corresponding capacity and incentive on the part of the industrial participants to do so. Fewer than 50 percent of the industrial participants interviewed reported any follow-on work stimulated by the collaborations. Overwhelmingly, OTA's industrial respondents did not feel that changes in institutional arrangements with the research performing centers would facilitate the commercialization process. Rather, they saw the principal barriers as being internal corporate problems: how companies can justify major investments in new manufacturing facilities in light of uncertain markets, how to adopt longer term planning horizons, and how to facilitate better communication between their R&D and manufacturing functions.

Thus, there appears to be a significant gap between the point at which government/university/industry collaborative materials research leaves off and the point at which industry is willing to begin to explore the commercial potential. Policy options that could help bridge this gap are discussed in the policy section below.

MILITARY ROLE IN ADVANCED MATERIALS DEVELOPMENT

Just as universities and Federal laboratories represent unique resources available to U.S. advanced materials companies, the substantial DoD and NASA investments in advanced materials for military and space applications can also contribute to the commercial competitiveness of U.S. firms.

At present, the military establishment is one of the largest customers of advanced materials, especially composites, and its use of these materials is expected to grow rapidly. DoD has committed itself to purchase 80 billion dollars' worth of weapons systems that will incorporate advanced composite components.

Composites have already been used in the Army's Apache and Black Hawk helicopters, Navy aircraft such as the AV-8B, the F-18, and the F-14, and the Air Force's F-15 and F-16. PMCs are currently in full-scale development for the Navy's V-22 Osprey, and are under considera-

Photo credit: McDonnell Douglas

The Navy AV-8B Aircraft.

tion for several systems including the Army's LHX helicopters and the Air Force's Advanced Tactical Fighter. Ceramics and composites of various kinds will also be enabling technologies in such new programs as the National Aerospace Plane (NASP) and the Strategic Defense Initiative (SDI).

Counting only basic and early applied R&D (budget categories 6.1-6.3A), DoD sponsors about 60 percent ($98 million of a total of $167 million in fiscal year 1987) of Federal advanced structural materials R&D in the United States, as shown in table 1-7. If military development, testing, and evaluation funds (as well as funds for classified programs) were included, this fraction would be much higher. Military research in advanced structural materials has aimed at achieving such goals as higher operating temperatures, higher toughness, lower radar observability, and reduced weight.

Today, it is clear that U.S. leadership in advanced composites technologies of all types stems from the substantial DoD and NASA investments in these materials over the past 25 years. U.S. companies have been able to leverage their resources by using DoD funds for R&D in these technologies. There are some areas of strong overlap between military and commercial sectors. These include basic research in materials synthesis, properties, and behavior, as well as certain applications, such as aircraft, in which the military and commercial performance requirements are similar. DoD has also instituted programs such as the Manufacturing Technologies (ManTech) program to develop low-cost manufacturing methods, a critical need for both military and commercial structures.

As a principal supporter of advanced materials R&D, the military has two primary policy goals relating to the technologies. The first is to prevent or slow their diffusion to Eastern bloc countries, and the second is to secure viable domestic sources of supply. In an era of rapid technology diffusion across national borders and the growing multinational character of advanced materials industries, these policy goals are increasingly in conflict with commercial interests. Major issues that will require resolution include export controls, controls on technical information, and government procurement practices.

As commercial markets for these materials continue to grow, effective balancing of military and commercial interests in advanced materials could become a critical factor in U.S. companies' competitiveness in these technologies.

Table 1-7.—U.S. Government Agency Funding for Advanced Structural Materials in Fiscal Year 1987
(millions of dollars)

Agency	Ceramics and ceramic matrix composites	Polymer matrix composites	Metal matrix composites	Carbon/carbon composites	Total
Department of Defense[a]	$21.5	$33.8	$29.7	$13.2	$ 98.2
Department of Energy	36.0	—	—	—	36.0
National Aeronautics and Space Administration	7.0	5.0	5.6	2.1	19.7
National Science Foundation	3.7	3.0	—	—	6.7
National Bureau of Standards	3.0	0.5	1.0	—	4.5
Bureau of Mines	2.0	—	—	—	2.0
Department of Transportation	—	0.2	—	—	0.2
Total	$73.2	$42.5	$36.3	$15.3	$167.3

[a] Includes only budget categories 6.1-6.3A.

SOURCE: OTA survey of agency representatives.

POLICY ISSUES AND OPTIONS

Perhaps the central finding of this assessment is that potential commercial end users of advanced materials, whose investment decisions are determined by expected profits, do not believe that use of advanced materials will be profitable within their planning horizon of 5 years. Thus, there is virtually no market pull on these technologies in the United States. While U.S. commercial end users have placed themselves in a relatively passive, or reactive role with respect to use of advanced materials, their competitors, notably the Japanese, have adopted a more aggressive, "technology push" strategy.

Ultimately, the future competitiveness of U.S. advanced materials industries in worldwide commercial markets depends on the investment decisions made within the industries themselves. These decisions are strongly affected by a variety of Federal policies and regulations.

It is useful to begin the policy discussion by considering what outcomes are likely if current trends continue.

Projections Based on a Continuation of the Status Quo

Because U.S. military markets will expand faster than commercial markets in the near term, the military role in determining the development agenda for advanced materials is likely to broaden. As explained above, military investments in advanced materials can be an asset to U.S. firms; however, they could also tend to direct resources toward development of high-performance, high-cost materials that are inappropriate for commercial applications.

Meanwhile, the reluctance of U.S. commercial end users to commit to advanced materials suggests that foreign firms will have an advantage in exploiting global markets as they develop. Almost certainly, a successful product using an advanced material produced abroad would stimulate a flurry of R&D activity among U.S. companies. However, given the lack of experience in this country with low-cost, high-volume fabrication technologies, it is not obvious that the United States could easily catch up.

The high cost of R&D, scale-up, and production of advanced materials, together with the poor near-term commercial prospects, will drive more and more U.S. companies to pool resources and spread risks through a variety of joint ventures, consortia, and collaborative research centers. Currently, many such collaborative centers are springing up across the United States. These centers will provide an excellent environment for conducting generic research and training of students. However, because of the high risks involved, they will not necessarily lead to more aggressive commercialization of advanced materials by participating companies.

Through acquisitions, joint ventures, and licensing agreements, the advanced materials industries will continue to become more multinational in character. Technology will flow rapidly between firms and across national borders. Critical advances will continue to come from abroad, and the flow of materials technology into this country will become as important as that flowing out. U.S. efforts to regulate these flows for national security reasons will meet increasing resistance from multinational companies intent on achieving the lowest production costs and free access to markets.

These scenarios suggest that there is reason to doubt whether the United States will be a world leader in manufacturing with advanced materials in the 1990s and beyond. The commercialization of these materials is essentially blocked because they do not meet the cost and performance requirements of potential end users. OTA finds that there are four general Federal policy objectives that could help to reduce these barriers:

1. Encourage long-term investment by advanced materials end users;
2. Facilitate government/university/industry collaboration in R&D for low-cost materials fabrication processes;
3. Facilitate more effective commercial exploitation of military R&D investments where possible; and
4. Build a strong advanced materials technology infrastructure.

Policy options for pursuing these objectives range from those with a broad scope, affecting many technologies, to those specifically affecting advanced materials. These options are not mutually exclusive, and most could be adopted without internal contradiction.

Encourage Long-Term Investment by Advanced Materials End Users

Greater investment in advanced materials by potential end users would generate more market pull on these technologies in the United States. The shortfall of long-term investment in advanced materials by potential end user companies is only one example of a more widespread shortfall found in many U.S. industries.

The climate for long-term industry investment is strongly affected by Federal policies and regulations, including tax policy, intellectual property law, tort law, and environmental regulations. Public debate regarding the relationships between these Federal policies and regulations and U.S. industrial competitiveness has given rise to a voluminous literature. Suggested policy changes include: providing tax incentives for long-term capital investments, reducing taxation on personal savings in order to make more investment capital available and thus reduce its cost, and comprehensive tort law reform aimed at making product liability costs proportional to proven negligence.

These policy options have implications far beyond advanced materials technologies, and an analysis of their effects is beyond the scope of this assessment.

Facilitate Government/University/Industry Collaboration in R&D for Low-Cost Materials Fabrication Processes

More than any other single barrier, the lack of reliable, low-cost fabrication processes inhibits the use of advanced structural materials in commercial applications. Due to the high costs of developing these processes, it is a fruitful area for collaborative research. Three major reservoirs of materials expertise are available to United States companies: 1) universities, 2) Federal laboratories, and 3) small high-technology firms.

Option 1: Establish a limited number of collaborative centers dedicated to advanced materials manufacturing technology.

Creation of a small number of collaborative centers in which manufacturing research and scale-up costs would be shared by government, university, and industry stakeholders, could increase industry incentives to invest in commercialization. These centers need not be new; they could be based at existing centers of excellence.

Option 2: Encourage large companies to work with small advanced materials firms, which have materials fabrication expertise, but lack the capital to explore its commercial potential.

Small advanced materials companies represent a technology resource that could make large materials supplier and user companies more competitive in the future. Whether through acquisitions, joint ventures or other financial arrangements, relationships with small materials companies can provide large companies with access to technologies that have commercial promise, but that are too risky for the large company to develop in-house. Expanding the Small Business Innovation Research (SBIR) program is one option for cultivating this resource.

Facilitate More Effective Commercial Exploitation of Military R&D Investments Where Possible

Military policy will continue to have a major impact on the domestic advanced materials industry. More effective exploitation of the military investment for commercial purposes, while protecting national security concerns, could lead to significant competitive advantages for U.S. firms involved in these technologies.

Export Controls

Early in 1987, the Department of Commerce proposed several changes in the administration of export controls intended to alleviate their impact on U.S. high-technology trade. Among these are proposals to remove technologies that have become available from many foreign sources from the control lists, and to reduce the review period for export license applications. These changes could be helpful, but some further steps should be considered.

Option 1: Increase representation by nondefense materials industries in policy planning for export controls.

Currently, advice for making export control policy decisions comes primarily from defense agency personnel and defense contractors. To achieve a better balance between military and commercial concerns, greater non-defense industry participation in this process is desirable. An industry advisory group such as the Materials Technology Advisory Council at the Department of Commerce could provide this perspective.

Option 2: Eliminate or loosen reexport controls.

The United States is currently the only nation that imposes controls on the reexport by other countries of products containing U.S.-made materials or components. Many countries view U.S. reexport controls as unwarranted interference in their political and commercial affairs, and this has led to a process of "de-Americanization" in which foreign companies avoid the use of U.S.-made materials and components. One option would be to eliminate the U.S. reexport restrictions entirely, while encouraging foreign trading partner nations to develop and maintain their own export controls for these products.

Option 3: Streamline and coordinate the various export control lists.

All of the various lists under which technologies are controlled should receive careful review for correctness and current relevance. These lists could also be coordinated more effectively. For example, the Departments of Commerce and State have overlapping legal and regulatory authority to control the export of MMC technology. The present system is extremely confusing to U.S. companies, which have experienced long delays in obtaining approval for export licenses. One option would be to have a single agency regulate both the export of MMC materials and technical data related to them.

Information Controls

Technical information about advanced materials is controlled under a complex regime of laws and regulations administered by the Departments of State, Commerce, and Defense. Currently, dissemination of advanced materials technical information can be controlled by: International Traffic in Arms Regulations (ITAR) of the Department of State; the dual-use technology restrictions of the Department of Commerce; the Defense Authorization Act of 1984; government contract restrictions; and Federal document classification systems. There are so many ways to restrict information that actual implementation of restrictions can appear arbitrary. Under some of these laws, regulations, and clauses, one can file for a license to export, and under others, there is no mechanism to permit export of the information. These controls have led to disruption of scientific meetings and to restriction of some advanced materials conference sessions to "U.S. only" participation.

Option 1: Simplify and clarify the various information restriction mechanisms.

Excessive restrictions on information flow can inhibit technology development and prevent technology transfer between the military and commercial sectors. Relying more on classification and less on the other more tenuous mechanisms of control (such as the Defense Authorization Act or contract clauses), could clarify some of the confusion.

Option 2: Make military materials databases more available to U.S. firms.

The most comprehensive and up-to-date information on advanced materials is now available only to government contractors through the Defense Technical Information Center (DTIC). DTIC contains a significant amount of information that is neither classified nor proprietary, but is still limited to registered users. Such information could be of value to U.S. commercial firms that are not government contractors.

Military Research in Manufacturing Technologies

Although military applications for advanced materials can generally tolerate higher costs for materials and processes than commercial applications, both could benefit greatly from research on low-cost processing methods. The desire to reduce procurement costs led DoD to implement its ManTech program, which includes projects devoted to development of many different materials and manufacturing technologies.

Option: Increase support for advanced materials manufacturing research through the ManTech program.

Development of low-cost manufacturing technologies would not only reduce military procurement costs, but could also hasten the commercial use of advanced materials technologies developed for the military. One mechanism to achieve this would be to augment the ManTech budget for those programs aimed at decreasing production costs and increasing reproducibility and reliability of advanced materials structures.

Procurement Practices

DoD constitutes a special market with unique materials requirements. However, like other customers, DoD seeks the widest variety of materials available at the lowest possible cost. It therefore employs regulatory means to simulate the conditions of commercial markets. This makes the participation by materials suppliers extremely dependent on defense regulations and policies, rather than on conventional economic criteria. Through its policies on dual sourcing, materials qualification, and domestic sourcing of advanced materials, DoD has a profound influence on the cost and availability of a variety of high-performance materials and technologies.

Option: Provide a clear plan for implementing legislation aimed at establishing domestic sources of advanced materials technology.

Uncertainties about how recent domestic sourcing legislation (particularly that relating to procurement of polyacrylonitrile (PAN)-based carbon fibers) will be implemented have caused much concern in the advanced composites community. In order to make intelligent investment decisions, U.S. carbon fiber suppliers will require a clear DoD plan including information on quantities to be purchased and the specific weapons systems involved.

Offsets

Offsets are a foreign policy-related marketing arrangement in which the foreign buyer of aircraft or other high-technology systems receives materials production technology from the U.S. system supplier as part of the sale. This can lead to a production capability abroad that is detrimental to the U.S. advanced materials technology base. Technology offsets are commonly required by foreign governments before bids from U.S. (or other) systems suppliers will be considered. In recent years, little attention has been paid to the effects of offsets.

Option: Initiate a thorough study on the effects of offsets on the competitiveness of U.S. advanced materials industries.

Build a Strong Advanced Materials Technology Infrastructure

For U.S. advanced materials suppliers and users to exploit technological developments rapidly, whether they originate in the United States or abroad, an infrastructure must be built up to reduce barriers to their use. In this context, a technology infrastructure encompasses the availability of basic scientific knowledge, technical data to support design and fabrication, and an adequate supply of trained personnel.

Option 1: Increase R&D funding levels to reduce the costs of advanced materials and improve their performance.

The development of low-cost fabrication processes that are capable of making large numbers of structures with reproducible properties is of primary importance.

Option 2: Develop a comprehensive and up-to-date database of collaborative R&D efforts in advanced materials at the Federal, regional, and State levels, including program goals and funding.

In recent years, a large number of research centers of excellence in advanced materials have sprung up with the aid of government funding at Federal, regional, and State levels. Although there are advantages to such a decentralized approach, the resulting dispersion of talent and resources also could preclude the formation of a "critical mass" necessary to solve the remaining technical and economic problems. Such a database would be an essential first step in bringing greater coordination to these efforts.

Option 3: Gather comprehensive information on current activities in government-funded R&D on advanced structural materials.

One persistent need identified by many industry sources is a central source of information on government projects in advanced materials. In general, this information does exist, but it is rarely in a form that is readily accessible to researchers. An oversight organization such as the National Critical Materials Council could help to gather and disseminate such information.

Option 4: Establish a mechanism for gathering business performance statistics on advanced materials industries.

It is difficult to evaluate the business trends of U.S. advanced materials industries because the statistics are aggregated with those of traditional materials industries. One alternative for correcting this situation would be to create separate Standard Industrial Classification (SIC) codes for advanced ceramics and composites so that statistics on production, imports, and exports can be systematically tracked.

Option 5: Step up person-to-person efforts to gather and disseminate data on international developments in advanced materials.

As several competitor countries around the world approach and exceed U.S. capabilities in advanced materials, it becomes imperative for U.S. companies to have prompt and reliable access to these overseas developments. Rather than engage in massive translation of technical publications, which may compete with private sector efforts, the best Federal approach may be to provide increased funding for U.S. scientists to visit laboratories abroad, encourage them to publish accounts of their experiences, and to disseminate this information to U.S. industry.

Option 6: Increase support for the development of standards for advanced materials.

It is very difficult to set standards in a field such as advanced materials in which technologies are evolving rapidly. However, timely development of standard test methods, production quality control standards, and product specification standards would greatly facilitate the manufacture of high-quality products at a lower cost. Several government and private sector organizations have begun to address this problem, but progress has been slow. Particularly important may be greater Federal support of efforts to establish international standards. If the United States fails to agree on standards or is forced to accept standards developed abroad, this could become a significant competitive disadvantage for U.S. companies.

Option 7: Increase the pool of trained materials scientists and engineers by providing increased funding for multidisciplinary university programs in advanced structural materials, and by providing retraining opportunities for technical personnel in the field.

Advanced materials industry sources contacted by OTA were nearly unanimous in their recommendation that more trained personnel are needed. Because materials science cuts across many traditional academic disciplines, multidisciplinary materials programs for students will be very important. Another important source of manpower will be retraining of designers and manufacturing engineers in the field who are unfamiliar with the new materials. Small businesses, professional societies, universities, and Federal laboratories could all play a role in providing such retraining services.

TWO VIEWS OF ADVANCED MATERIALS POLICIES

Congress and the Reagan Administration have adopted conflicting views of policymaking with respect to advanced materials. The crux of the conflict is whether the Federal Government should establish a high-level plan for advanced materials technology development, or whether goals and priorities should be established in a decentralized fashion by the principal funding agencies according to their various missions.

The United States has long had a decentralized approach to advanced materials policy. To a great extent, the major agencies that engage in materials R&D (DoD, DOE, NASA, and NSF) sponsor projects in the context of their distinct missions.

In the congressional view, the growing technological capabilities of the United States' competitors have underscored the urgency of a nationally coordinated approach to advanced materials R&D. This view is expressed in the National Critical Materials Act of 1984, in which Congress established the National Critical Materials Council (NCMC) in the Executive Office of the President. The NCMC is charged with the responsibility of working with the principal funding agencies and the Office of Management and Budget to define national priorities for materials R&D, and to coordinate the various agency efforts. Advocates of a national materials policy point to the apparent capacity of Japan to identify key technologies for the future and pursue their development by means of a coordinated, government/industry effort. Advanced ceramics have been a high-visibility example.

In the Administration's view, it is not appropriate for the government to engage in advanced materials planning; this is viewed as putting the government in a position of "picking winners"—which, according to current thinking, is best left to the private sector. Because different agencies have different missions and requirements for materials, determination of R&D priorities is best made at the agency level. Administration critics of the national materials policy concept maintain that attempts to make materials policy above the agency level risk the worst aspects of Japanese policies, the overbearing bureaucracy, without achieving the best effect, the commitment and coordination of industry. In their view, the congressionally mandated NCMC is redundant with existing interagency committees.

While the Reagan Administration has resisted the concept of strategic advanced materials planning for commercial competitiveness, it has embraced it with regard to national defense needs. DoD is currently preparing a comprehensive policy initiative aimed at preserving the U.S. defense industrial base. This initiative will target a portfolio of technologies, including machine tools, bearings, castings, semiconductors, and advanced composites, for support. Issues such as technological obsolescence, availability of trained personnel, foreign acquisitions of U.S. companies, international cooperation, and government/university/industry collaboration are being addressed.

A national approach to a materials program has several potential advantages. It can provide a focus for the efforts of individual agencies and collaborative government/industry projects. It can provide a continuity of funding in a given area as fashionable R&D areas change from year to year. Finally, it can provide a rationale for committing large amounts of resources for expensive manufacturing development and demonstration programs. To be successful, such a national program should not be a "top-down" approach, but should be structured with consultation and participation of the university, Federal laboratory, and industry community which will ultimately implement it.

Such a national approach also has disadvantages. It may focus on the wrong materials, and be too inflexible to capitalize on new opportunities that arise. It may tie up resources and manpower in long-term programs that are better invested elsewhere. Finally, because it cannot address the cost and performance requirements of materials in actual commercial markets, it may fail to produce materials or processes that are economically attractive to end users.

The debate surrounding national materials policy has suffered from the lack of a clear definition of what such a policy would entail. Whereas policy goals such as conservation of scarce materials or reliable access to strategic minerals are easily understood in the context of conventional materials, it is much more difficult to define national goals for advanced materials. To succeed in its task, the NCMC will need to establish a more precise definition of these goals, and to develop high-level Administration commitment to the concept of a national materials policy.

Pending the resolution of differences between Congress and the Administration regarding the role of the NCMC, there are three futher functions that the NCMC could perform:

- Serve as a point of contact to receive and monitor industry concerns relating to advanced materials

An organization such as the NCMC could provide a forum for interaction between industry and the Federal Government on issues relating to advanced materials, particularly those that transcend the purview of any particular Federal agency. This could promote better mutual understanding of industry and government perspectives on advanced materials development, and could eventually lead to the development of a consensus on promising future directions.

- Serve as an information source and a referral center regarding advanced materials

U.S. advanced materials programs and expertise are widely dispersed throughout various agencies and laboratories. There is currently no definitive source of information that can provide an overview of ongoing efforts. An organization such as the NCMC could gather this information from the relevant agencies, analyze it, and disseminate it.

- Serve as a broker for resolving conflicts between military and commercial agency goals for advanced materials

There are materials issues that transcend individual agencies and that could be resolved by an organization above the agency level. For instance, the export control responsibility for regulating advanced materials and information relating to them is currently spread over the Departments of Commerce, State, and Defense, a situation that is very confusing to industry. An organization such as the NCMC could work with the National Security Council to help simplify and clarify the various agencies' responsibilities.

ADVANCED MATERIALS POLICIES IN A BROADER CONTEXT

Ceramic and composite structural materials clearly represent great potential opportunities for the U.S. economy. However, advanced materials are not unique in their importance to the future competitiveness of U.S. manufacturing industries. Other technologies, including microelectronics, computers, robotics, and biotechnology will also be important. These technologies face similar competitive challenges, and many of the policy objectives and options discussed above could benefit all of them. As such, it may be most appropriate to address the commercialization of advanced materials technologies as part of a broader policy package aimed at achieving greater investment and productivity in the manufacturing sector as a whole.

Chapter 2

Ceramics

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Chapter 2
Ceramics

FINDINGS

The broad class of materials known as ceramics includes all solids that are neither metallic nor organic. Advanced structural ceramics differ from conventional ceramic consumer goods in that they are made from extremely pure, microscopic powders that are consolidated at high temperatures to yield a dense, durable structure. Compared with metals, advanced structural ceramics have superior wear resistance, high-temperature strength, and chemical stability. They generally have lower electrical and thermal conductivity, and lower toughness. The low toughness of ceramics (brittleness) causes them to fail suddenly when the applied stress is sufficient to propagate cracks that originate at flaws in the material. The actual stress level at which this occurs can be very high if the flaw sizes are small. However, unpredictable failure caused by poor control over flaw populations remains a major handicap to the use of structural ceramics in load-bearing applications.

There are several methods that can reduce the sensitivity of ceramics to flaws. Incorporation of ceramic particulates, whiskers, or continuous fibers in a ceramic matrix can produce a composite that absorbs more energy during fracture than the matrix alone, and is therefore tougher. A different approach is the application of a thin ceramic coating to a metal substrate. This yields a component with the surface properties of a ceramic combined with the high toughness of metal in the bulk.

Advanced ceramic components are more expensive than the metal components they would replace. This is primarily due to the high cost of processes that are capable of fabricating ceramics reliably and reproducibly. Finishing and machining operations to form the part to its final shape are expensive due to the extreme hardness of the material. Nondestructive testing to ensure reliability is also a major component of production costs. Therefore, development of processes that can reliably fabricate a component to final net shape is crucial. In many applications, thin coatings of a high-performance ceramic on a metal substrate may offer the best compromise between cost and performance.

Applications and Market Opportunities

Advanced structural ceramics are in production for wear parts, cutting tools, bearings, filters, and coatings. Ceramics are also in limited production (in Japan) in discrete engine components such as turbocharger rotors, glow plugs, and precombustion chambers. Current military applications in the United States include radomes, armor, and infrared windows.

Near-term production (next 10 to 15 years) is expected in advanced bearings, bioceramics, construction applications, heat exchangers, electrochemical devices, discrete components in automobile engines, and military engines. Especially high growth may be seen in bioceramics for dental and orthopedic implants, and chemically bonded ceramics for construction applications.

Far-term applications (beyond 15 years) are those that require solution of major technical and economic problems. These include an advanced automotive turbine engine, an advanced ceramic diesel (although ceramics could be used in military versions of these engines at an earlier date), some electrochemical devices, military components, and heat exchangers. A variety of other turbine engines, especially turbines for aircraft propulsion and for utility-scale power generation, should also be categorized as far-term.

Research and Development Priorities

The following hierarchy of R&D priorities is based on the technical barriers that must be overcome before ceramics can be used in the applications discussed above.

Processing Science

This is the key to understanding how processing variables such as temperature, composition, and particle size distribution are connected to the desired final properties of the ceramic.

Environmental Behavior

In many applications, ceramics are required to withstand high-temperature, corrosive, or erosive environments. Information on the behavior of ceramics in these environments is essential to predict the service life of ceramics in those applications.

Reliability

The reliability of advanced ceramics and ceramic composites is the single most important determinant of success in any application. Progress requires advances in design of brittle materials, process control, nondestructive evaluation, understanding crack growth processes, and life prediction.

Ceramic Composites

These novel materials offer an exciting opportunity to increase the strength and toughness of ceramics.

INTRODUCTION

Ceramics are nonmetallic, inorganic solids. By far the most common of terrestrial materials, ceramics made of sand and clay have been used for many thousands of years for brick, pottery, and artware. However, modern structural ceramics bear little resemblance to these traditional materials; they are made from extremely pure, microscopic powders that are consolidated at high temperatures to yield a dense and durable structure.

The U.S. market for advanced structural ceramics in 1987 was $171 million.[1] In the next 10 to 15 years, however, the market opportunities for structural ceramics are expected to expand rapidly (table 2-1) such that by the year 2000, the U.S. market alone is projected to be between $1 billion and $5 billion per year.[2]

Properties of Ceramics

The properties of some common structural ceramics are compared with those of metals in table 2-2. In general, ceramics have superior high-temperature strength, higher hardness, lower density, and lower thermal conductivity than metals. The principal disadvantage of using ceramics as structural materials is the sensitivity of their strength to extremely small flaws, such as cracks, voids, and inclusions. Flaws as small as 10 to 50 micrometers can reduce the strength of a ceramic structure to a few percent of its theoretical strength. Because of their small sizes, the strength-controlling flaws are usually very difficult to detect and eliminate.

The flaw sensitivity of ceramics illustrates the importance of carefully controlled processing and finishing operations for ceramic components. However, even with the most painstaking efforts, a statistical distribution of flaws of various sizes

Table 2-1.—Some Future Applications of Structural Ceramics

Application	Performance advantages	Examples
Wear parts seals bearings valves nozzles	High hardness, low friction	Silicon carbide, alumina
Cutting tools	High strength, hot hardness	Silicon nitride
Heat engines diesel components gas turbines	Thermal insulation, high temperature strength, fuel economy	Zirconia, silicon carbide, silicon nitride
Medical implants hips teeth joints	Biocompatibility, surface bond to tissue, corrosion resistance	Hydroxylapatite, bioglass, alumina, zirconia
Construction highways bridges buildings	Improved durability, lower overall cost	Advanced cements and concretes

SOURCE: Office of Technology Assessment, 1988.

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[1] Up from $112 million in 1985, according to data supplied by Business Communications Co., Inc. of Norwalk, CT. This includes wear parts, cutting tools, heat exchangers, engine components, bioceramics, and aerospace applications.

[2] Greg Fischer, "Strategies Emerge for Advanced Ceramic Business," *American Ceramic Society Bulletin* 65(1):39, 1986.

Table 2-2.—Comparison of Physical and Mechanical Properties of Common Structural Ceramics With Steel and Aluminum Alloys. SiC: silicon carbide; Si_3N_4: silicon nitride; ZrO_2: zirconia

Material	Density[a] (g/cm³)	Room temperature[a] strength (MPa)	Strength[a] at 1,095° C (MPa)	Hardness[b] (kg/mm²)	Thermal conductivity[a] 25°/1,100° (W/m° C)
Various sintered SiC materials	3.2	340-550 (flexure)	340-550 (flexure)	2,500-2,790	85/175
Various sintered Si_3N_4 materials	2.7-3.2	205-690 (flexure)	205-690 (flexure)	2,000[c]	17/60
Transformation toughened ZrO_2	5.8	500-1,250 (flexure)[c]	—	1,300-1,635[c]	1.7/3.5
Steels (4100, 4300, 8600, and 5600 series)	7-8	1,035-1,380 (tensile yield)	useless	450-650	43
Aluminum alloy	2.5	415-895 (tensile yield)	useless	100-500	140-225

NOTE: 1 MPa = 145 psi = 0.102 Kg/mm².

SOURCES: [a] R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," *Materials Science and Engineering* 71:227-249, 1985.
[b] Elaine P. Rothman, "Ultimate Properties of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.
[c] "Ceramic Application and Design," *Ceramic Industry*, February 1988, pp. 29-50.

and locations will always exist in any ceramic structure. Even identically prepared ceramic specimens will display a distribution of strengths, rather than a single value. Design with ceramics, unlike design with metals, is therefore a statistical process, rather than a deterministic process.

Ceramic failure probability is illustrated in figure 2-1. The curve on the right in figure 2-1a represents the distribution of strengths in a batch of identically prepared ceramic components. The curve on the left is the distribution of stresses that these components are subjected to in service. The overlap between the two curves, in which the stress in service exceeds the strength of the ceramic, determines the probability that the part will fail.

There are several ways to reduce the probability of failure of the ceramic. One is to shift the strength distribution curve to the right by elimination of the larger flaws, as shown in figure 2-1b. A second way is to use nondestructive testing or proof testing to weed out those components with major flaws. This leads to a truncation of the strength distribution, as shown in figure 2-1c. Proof testing of each individual component, although widely used in the industry today, is expensive and can introduce flaws in the material that were not there originally.

A third way to reduce failure probability is to design the microstructure of the ceramic so that it has some resistance to fracture (increased toughness), and hence, some tolerance to defects. Toughness is a measure of the energy required to fracture a material in the presence of flaws. For a ceramic component under stress, the toughness determines the critical flaw size that will lead to catastrophic failure at that stress. In fact, the critical flaw size increases with the square of the toughness parameter; thus, an increase in the material toughness of a factor of three leads to a ninefold increase in the flaw size tolerance.

Reduction in the flaw sensitivity of ceramics is especially important for applications involving a hostile environment, which can introduce strength-degrading defects and thus negate all efforts to ensure reliability by identifying or eliminating the largest preexisting flaws.

Three recent developments have been shown to improve the toughness of ceramics: microstructure design, transformation toughening, and composite reinforcement.

Microstructure Design

The toughness of monolithic ceramics can be improved considerably by refinement of the polycrystalline grain size and shape. The presence of elongated fibrous grains, especially in ceramics based on silicon nitride, has been shown to increase toughness by as much as a factor of 2 over other monolithic ceramics, such as silicon carbide and aluminum oxide.[3]

Numerous mechanisms have been proposed to account for the observed toughening: crack deflection, microcracking, residual stresses, crack pinning, and crack bridging. It is likely that several of these mechanisms operate simultaneously in these materials. The high toughness is accompanied by high strength, both of which result from the modified microstructure.

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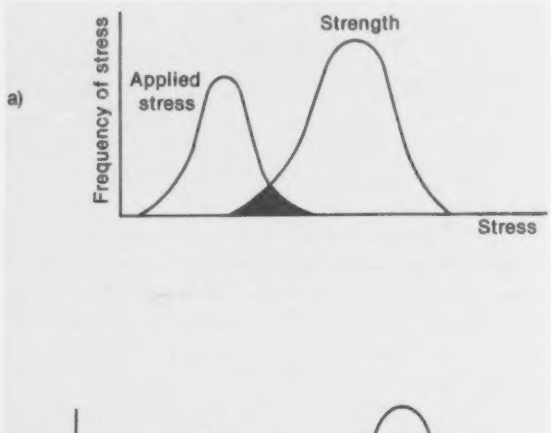
[3] *Nitrogen Ceramics*, F.L. Riley (ed.) (Boston and The Hague: Martinus Nijhoff Publishers, 1983).

Figure 2-1.—Probability of Failure of a Ceramic Component



The probability of failure of a ceramic component is the overlap between the applied stress distribution and the material strength distribution, as shown in (a). This probability can be reduced by reducing the flaw size (b), or truncation of the strength distribution through proof testing (c).

SOURCE: R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," *Materials Science and Engineering* 71:227-249, 1985.

Transformation Toughening

Transformation toughening, a relatively new approach to achieving high toughness and strength in ceramics, has great potential for increasing the use of ceramics in wear-resistance applications. The key ceramic material is zirconia (zirconium oxide).

Zirconia goes through a phase transformation from the tetragonal to the monoclinic crystal form while cooling through a temperature of about 2100° F (1150° C). This phase transformation is accompanied by an increase in volume of 3 percent, similar to the volume increase that occurs when water freezes. By control of composition, particle size, and heat treatment cycle, zirconia can be densified at high temperature and cooled such that the tetragonal phase is maintained down to room temperature.

When a load is applied to the zirconia and a crack starts to propagate, the high stresses in the vicinity of the crack tip catalyze the transformation of adjacent tetragonal zirconia grains to the monoclinic form, causing them to expand by 3 percent. This expansion of the grains around the crack tip compresses the crack opening, thereby preventing the crack from propagating.

Ceramic Matrix Composites

A variety of ceramic particulates, whiskers (high-strength single crystals with length/diameter ratios of 10 or more), and fibers may be added to the host matrix material to generate a composite with improved fracture toughness.

The presence of these reinforcements appears to frustrate the propagation of cracks by at least three mechanisms. First, when the crack tip encounters a particle or fiber that it cannot easily break or get around, it is deflected off in another direction. Thus, the crack is prevented from propagating cleanly through the structure. Second, if the bond between the reinforcement and the matrix is not too strong, crack propagation energy can be absorbed by pullout of the fiber from its original location. Third, fibers can bridge a crack, holding the two faces together, and thus prevent further propagation.

Table 2-3 presents the fracture toughness and critical flaw sizes (assuming a typical stress of 700 megapascals [MPa], or about 100,000 pounds per square inch [psi]) of a variety of ceramics and compares them with some common metals. The toughness of monolithic ceramics generally falls in the range of 3 to 6 MPa-m$^{1/2}$, corresponding to a critical flaw size of 18 to 74 micrometers. With transformation toughening or whisker dispersion, the toughness can be increased to 8 to 12 MPa-m$^{1/2}$ (the critical flaw size is 131 to 294 micrometers); the toughest ceramic matrix composites are continuous fiber-reinforced glasses, at 15 to 25 MPa-m$^{1/2}$. In these glasses, strength appears to be *independent* of preexisting flaw size and is thus an intrinsic material property. By comparison, metal alloys such as steel have toughnesses of more than 40 MPa-m$^{1/2}$, more than 10 times the values of monolithic ceramics; the toughness of some alloys may be much higher.

Table 2-3.—Fracture Toughness and Critical Flaw Size of Monolithic and Composite Ceramic Materials Compared With Metals.[a] Al_2O_3: alumina; LAS: lithium aluminosilicate; CVD: chemical vapor deposition

Material	Fracture toughness (MPa• m$^{1/2}$)	Critical flaw size (micrometers)
Conventional microstructure:		
Al_2O_3	3.5-4.0	25-33
Sintered SiC	3.0-3.5	18-25
Fibrous or interlocked microstructure:		
Hot pressed Si_3N_4	4.0-6.0	33-74
Sintered Si_3N_4	4.0-6.0	33-74
SiAlON	4.0-6.0	33-74
Particulate dispersions:		
Al_2O_3TiC	4.2-4.5	36-41
Si_3N_4-TiC	4.5	41
Transformation toughening:		
ZrO_2-MgO	9-12	165-294
ZrO_2-Y_2O_3	6-9	74-165
Al_2O_3-ZrO_2	6.5-15	86-459
Whisker dispersions:		
Al_2O_3-SiC	8-10	131-204
Fiber reinforcement:[b]		
SiC in borosilicate glass	15-25	
SiC in LAS	15-25	
SiC in CVD SiC	8-15	
Aluminum[c]	33-44	
Steel[c]	44-66	

[a] Assumes a stress of 700 MPa (~100,000 psi).
[b] The strength of these composites is independent of preexisting flaw size.
[c] The toughness of some alloys can be much higher.

SOURCES: David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985; and Elaine P. Rothman, "Ultimate Properties of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

The critical flaw size gives an indication of the minimum flaw size that must be reliably detected in any nondestructive evaluation (NDE) to ensure reliability of the component. Most NDE techniques cannot reliably detect flaws smaller than about 100 micrometers (corresponding to a toughness of about 7 MPa-m$^{1/2}$). Toughnesses of at least 10 to 12 MPa-m$^{1/2}$ would be desirable for most components.

Ceramic Coatings

The operation of machinery in hostile environments (e.g., high temperatures, high mechanical loads, or corrosive chemicals) often results in performance degradation due to excessive wear and friction, and productivity losses due to shutdowns caused by component failure. Frequently, the component deterioration can be traced to deleterious processes occurring in the surface region of the material. To reduce or eliminate such effects, ceramic coatings have been developed to protect or lubricate a variety of substrate materials, including metals, ceramics, and cermets (ceramic-metal composites).

The coating approach offers several advantages. First, it is possible to optimize independently the properties of the surface region and those of the base material for a given application. Second, it is possible to maintain close dimensional tolerances of the coated workpiece in that very thin coatings (of the order of a few micrometers) are often sufficient for a given application. Third, there are significant cost savings associated with using expensive, exotic materials only for thin coatings and not for bulk components. Use of coatings can thereby contribute to the conservation of strategically critical materials. Fourth, it is often cheaper to recoat a worn part than to replace it.

These advantages have led to widespread industry acceptance and applications. For instance, coatings of titanium nitride, titanium carbide, and alumina are used to extend the useful life of tungsten carbide or high-speed steel cutting tools by a factor of 2 to 5.[4] In 1983, annual sales of coated cutting tools reached about $1 billion.[5]

Ceramic coatings are also finding wide application in heat engines. Zirconia coatings of low thermal conductivity are being tested as a thermal barrier to protect the metal pistons and cylinders of advanced diesel engines. In turbine engines, insulative zirconia coatings have been found to improve performance by permitting combustion gas temperatures to be increased by several hundred degrees Fahrenheit without increasing the temperature of air-cooled metal components or the complexity of the engine.[6] Ceramic coatings are also being used to provide an oxidation barrier on turbine blades and rings.

Progress in the use of ceramic coatings in these and other applications suggest that further research on new coatings and deposition processes is likely to yield a high payoff in the future.

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[4] David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985.

[5] U.S. Department of Commerce, Bureau of the Census, Census of Manufacturing, Fuels, and Electric Energy Consumed, 1984.

[6] Tom Strangman, Garrett Turbine Engine Co., personal communication, August 1986.

DESIGN, PROCESSING, AND TESTING

It is in the nature of advanced structural materials that their manufacturing processes are additive rather than subtractive. Ideally, the materials are not produced in billets or sheets that are later rolled, cut, or machined to their final shape; rather, in each case the material is formed to its final shape in the same step in which the microstructure of the material itself is formed.

Because of the severity of joining problems, the ceramics designer is always conscious of the need to consolidate as many components as possible together in a single structure. Although consolidation cannot always be achieved (expensive grinding or drilling is often required), to a great extent, the promise of advanced materials lies in the possibility of net-shape processing, thereby eliminating expensive finishing and fastening operations.

Ceramics Design

Designing with ceramics and other brittle materials is very different from designing with metals, which are much more tolerant of flaws. In practice, ceramic structures always contain a distribution of flaws, both on the surface and in the bulk. Ceramic designs must avoid local stress concentrations under loading, which may propagate cracks originating at the flaws.

One serious barrier to the use of ceramics is the lack of knowledge among designers of the principles of brittle material design. Greater emphasis needs to be placed on brittle materials in college curricula. Courses at the college level and minicourses for continuing education on design for brittle materials should be offered and publicized.[7]

A second serious barrier is the poor characterization of commercially available ceramics for design purposes. The data are inadequate because the mechanical, thermal, and chemical properties of ceramic materials vary with the method of manufacture as well as the test method. Both carefully controlled and documented processing procedures and standard test methods, as discussed in chapter 5, will be required to give designers the confidence that consistent properties at a useful level can be obtained at a predictable cost.

Processing of Ceramics

The production of most ceramics, including both traditional and advanced ceramics, consists of the following four basic process steps: powder preparation, forming, densification, and finishing. The most important processing techniques involved in these steps are identified in table 2-4.

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[7] Specific proposals for improving ceramics education are given in the report of the Research Briefing Panel on Ceramics and Ceramic Composites (Washington, DC: National Academy Press, 1985).

Table 2-4.—Common Processing Operations for Advanced Ceramics

Operation	Process	Examples
Powder preparation	Synthesis	SiC
	Sizing	Si_3N_4
	Granulating	ZrO_2
	Blending	
	Solution chemistry	Glasses
Forming	Slip casting	Combustors, stators
	Dry pressing	Cutting tools
	Extrusion	Tubing, honeycomb
	Injection molding	Turbocharger rotors
	Tape casting	Capacitors
	Melting/casting	Glass ceramics
Densification	Sintering	Al_2O_3
	Reaction bonding	Si_3N_4
	Hot pressing	Si_3N_4, SiC, BN
	Hot isostatic pressing	Si_3N_4, SiC
Finishing	Mechanical	Diamond grinding
	Chemical	Etching
	Radiation	Laser, electron beam
	Electric	Electric discharge

SOURCE: Office of Technology Assessment, 1988

Powder Preparation

Although most of the basic raw materials for ceramics occur abundantly in nature, they must be extensively refined or processed before they can be used to fabricate structures. The entire group of silicon-based ceramics (other than silica) does not occur naturally. Compositions of silicon carbide, silicon nitride, and sialon (an alloy of silicon nitride with aluminum oxide in which aluminum and oxygen atoms substitute into silicon and nitrogen lattice positions, respectively) must all be fabricated from gases or other ingredients. Even minerals that occur naturally, such as bauxite, from which alumina is made, and zircon sands, from which zirconia is derived, must be processed before use to control purity, particle size and distribution, and homogeneity.

The crucial importance of powder preparation has been recognized in recent years. Particle sizes and size distributions are critical in advanced ceramics to produce uniform green (unfired) densities, so that consolidation can occur to produce a fully dense, sintered, ceramic part.

Various dopants or sintering aids are added to ceramic powders during processing. Sinterability can be enhanced with dopants, which control particle rearrangement and diffusivities. These dopants permit sintering at lower temperatures and/or faster rates. Dopants are also used to control grain growth or achieve higher final densities.

The use of dopants, although providing many beneficial results, can also have a detrimental influence on the material properties. Segregation of dopants at the grain boundaries can weaken the final part, and final properties such as conductivity and strength may differ significantly from those of the pure material.

Forming

Ceramic raw materials must be formed and shaped before firing. The forming process often determines the final ceramic properties. The important variables in the forming step are particle shape, particle packing and distribution, phase distribution, and location of pores.

Forming processes for ceramics are generally classified as either cold forming or hot forming. The major cold forming processes include slip casting, extrusion, dry pressing, injection molding, tape casting, and variations of these. The product of such processes is called a green body, which may be machined before firing. The homogeneity of the cold-formed part determines the uniformity of shrinkage during firing.

Hot forming processes combine into one step the forming and sintering operation to produce simple geometric shapes. These processes include hot pressing (in which pressure is applied along one direction) and hot isostatic pressing (HIPing, in which pressure is applied to the ceramic from all directions at once).

Densification

Sintering is the primary method for converting loosely bonded powder into a dense ceramic body. Sintering involves consolidation of the powder compact by diffusion on an atomic scale. Moisture and organics are first burned out from the green body, and then, at the temperature range at which the diffusion process occurs, matter moves from the particles into the void spaces between the particles, causing densification and resulting in shrinkage of the part. Combined with forming techniques such as slip casting, sintering is a cost-effective means of producing intricate ceramic components. Its drawback lies in the need to use additives and long sintering times to achieve high densities. The complications introduced by dopants have been noted above in the discussion of powders.

Finishing

This step involves such processes as grinding and machining with diamond and boron nitride tools, chemical etching, and laser and electric discharge machining. The high hardness and chemical inertness of densified ceramics make the finishing operations some of the most difficult and expensive in the entire process. Grinding alone can account for a large fraction of the cost of the component. In addition, surface cracks are often introduced during machining, and these can reduce the strength of the part and the yields of the fabrication process.

Near-Net-Shape Processing

Near-net-shape processing describes any forming process that gives a final product that requires little or no machining. Typically, ceramics shrink to about two-thirds of their green body volume upon sintering. This shrinkage makes it extremely difficult to fabricate ceramics to final net shape. However, if the green body ceramic is machined prior to densification, a near-net-shape part can be obtained. Hot isostatic pressing and ceramic coatings can also yield parts that do not require subsequent machining.

Reaction bonding is a near-net-shape process that has undergone considerable development, particularly for silicon nitride. In this process, green body compacts of finely divided silicon powder are reacted with nitrogen gas to produce silicon nitride. In reaction bonding, the spaces between the silicon powder particles in the green body are filled with silicon nitride reaction product as the reaction proceeds, so no shrinkage occurs. Reaction bonding can also be used to produce ceramic composites with excellent properties because this process avoids damage to reinforcement fibers or whiskers caused by shrinkage during the sintering step.

Near-net-shape processes that are currently used for metals include powder metallurgy and advanced casting techniques. Because metals are in direct competition with ceramics in many applications, near-net-shape processing of ceramics must continue to be a high-priority research area if advanced ceramics are to be cost-competitive.

Ceramic Matrix Composites

Ceramic matrix composites (CMCs) may consist of: randomly oriented ceramic whiskers within a ceramic matrix; continuous fibers oriented within a ceramic matrix; or dissimilar particles dispersed in a matrix with a controlled microstructure. The potential benefits of ceramic composites include increased fracture toughness, high hardness, and improved thermal shock resistance. Processing methods for particulate-reinforced composites are similar to those for monolithic ceramics, and so are not discussed in this section.

Whisker Reinforcement

Ceramic whiskers are typically high-strength single crystals with a length at least 10 times greater than the diameter. Silicon carbide is the most common whisker material. Currently, whisker-reinforced CMCs are fabricated by uniaxial hot pressing, which substantially limits size and shape capabilities and requires expensive diamond grinding to produce the final part. Although hot isostatic pressing has the potential to permit fabrication of complex shapes at moderate cost, this technique requires procurement of expensive capital equipment and extensive process development.

Continuous Fiber Reinforcement

The primary fibers available for incorporation into a ceramic or glass matrix are carbon, silicon carbide, aluminum borosilicate, and mullite. Currently, glass matrix composites are more developed than their ceramic analogs. These composites are far tougher than unreinforced glasses, but are limited to service temperatures of 1100° to 1300° F (593° to 704° C). Service temperatures up to 2000° to 2200° F (1093° to 1204° C) may be obtained with glass-ceramic matrices that crystallize upon cooling from the process temperature.[8] Carbon matrix composites have the highest potential use temperature of any ceramic, exceeding 3500° F (1927° C). However, they oxi-

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[8] Karl M. Prewo, J.J. Brennan, and G.K. Layden, "Fiber-Reinforced Glasses and Glass-Ceramics for High Performance Applications," *American Ceramic Society Bulletin* 65(2):305, 1986.

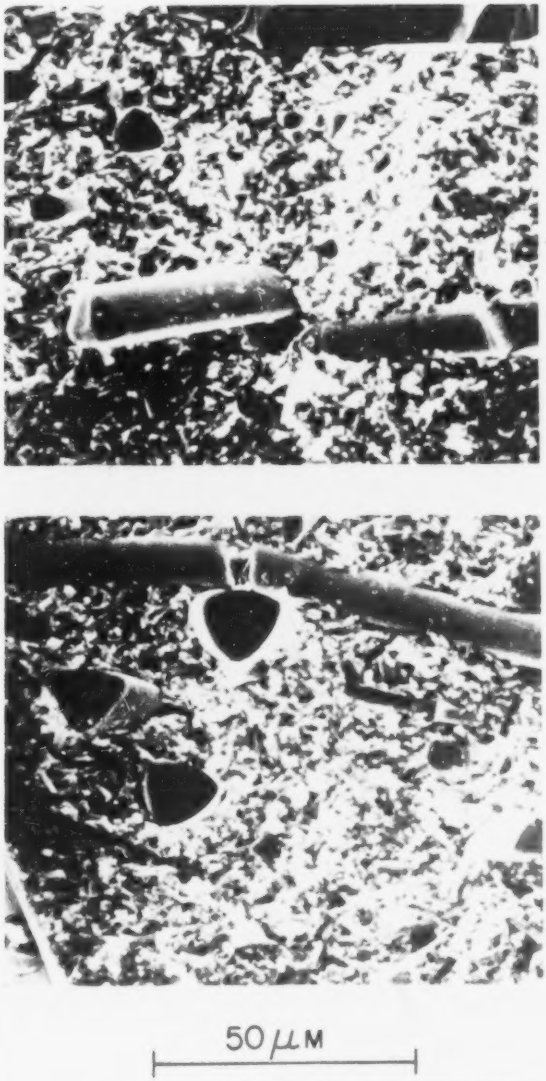

Photo credit: Los Alamos National Laboratory

Fracture surface of a composite formed by hot-pressing silicon nitride powder with 30 percent by volume silicon carbide whiskers.

dize readily in air at temperatures above about 1100° F (593° C), and require protective ceramic coatings if they are to be used continuously at high temperature.[9]

Photo credit: United Technologies Research Center

Tensile fracture surface for Nicalon SiC fiber-reinforced glass ceramic.

Fabrication of CMCs reinforced with continuous fiber is currently of a prototype nature and is very expensive. Several approaches are under development:

- the fibers are coated with ceramic or glass powder, laid up in the desired orientation, and hot pressed;
- fibers or woven cloth are laid up, and are then infiltrated by chemical vapor deposition (CVD) to bond the fibers together and fill in a portion of the pores;
- fibers are woven into a three-dimensional preform, and are then infiltrated by CVD; and
- a fiber preform is infiltrated with a ceramic-yielding organic precursor, and is then heat-treated to yield a ceramic layer on the fibers. This process is repeated until the pores are minimized.

Considerable R&D will be necessary to optimize fabrication and to decrease the cost to levels acceptable for most commercial applications.

Ceramic Coatings

Many different processes are used in the fabrication of ceramic coatings and in the modification of surfaces of ceramic coatings and monolithic ceramics. Table 2-5 lists some of the more important processes.

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[9] Joel Clark, et. al., "Potential of Composite Materials To Replace Chromium, Cobalt, and Manganese in Critical Applications," a contractor report prepared for the Office of Technology Assessment, 1984.

The choice of a particular deposition process or surface modification process depends on the desired surface properties. Table 2-6 lists some of the coating characteristics and properties that are often considered desirable. Additional considerations that can influence the choice of coating process include the purity, physical state, and toxicity of the material to be deposited; the deposition rate; the maximum temperature the substrate can reach; the substrate treatment needed to obtain good coating adhesion; and the overall cost.

For most coating processes, the relationships between process parameters and coating prop-

Table 2-5.—Selected Processes for the Production of Ceramic Coatings and for the Modification of Ceramic Surfaces

Process category	Process class	Process
Ceramic coating processes:		
Low gas pressure ("vacuum") processes	Chemical vapor deposition (CVD)	Pyrolysis Reduction (plasma assisted) Decomposition (plasma assisted) Polymerization (plasma induced)
	Physical vapor deposition (PVD)	Evaporation (reactive, plasma assisted) Sputtering (reactive, plasma assisted) Plasma-arc (random, steered) Ion beam assisted co-deposition
	Low pressure plasma spraying	Plasma discharge spraying
Processes at elevated gas pressures	Plasma spraying	Plasma arc spraying
	Flame spraying	Combustion flame spraying
Liquid phase epitaxy processes	Wetting process	Dip coating (e.g., Sol-Gel) Brush coating
	Spin-on coatings	Reverse-roller coating
Electrochemical processes	Electrolytic deposition	Cation deposition
	Electrophoretic deposition	Charged colloidal particle deposition
	Anodization	Anion oxidation in electrolytes
	Electrostatic deposition	Charged liquid droplet deposition
Processes for the modification of ceramic surfaces:		
Particle implantation processes	Direct particle implantation	Energetic ion or atom implantation in solids
	Recoil particle implantation	Recoil atom (ion) implantation in solids
Densification and glazing processes	Laser beam densification and glazing	CW-laser power deposition Pulsed-laser power deposition
	Electron beam densification and glazing	Energetic electron beam power deposition
Chemical reaction processes	Gaseous anodization processes	Ion nitriding Ion carburizing Plasma oxidation
	Disproportionation processes	Deposition of molecular species Formed in gas phase
Conversion processes	Thermal diffusion	Diffusion of material from surface into bulk of substrate
Etching processes	Chemical etching	Acidic solutions; lye etching
	Ion etching	Sputter process
Mechanical processes	Grinding Peening Polishing	

SOURCE: Manfred Kaminsky, Surface Treatment Science International, Hinsdale, IL.

Table 2-6.—Characteristics and Properties of Ceramic Coatings Often Considered Desirable

Good adhesion
Precise stoichiometry (negligible contamination)
Very dense (or very porous) structural morphology
Thickness uniformity
High dimensional stability
High strength
High fracture toughness
Internal stresses at acceptable levels
Controlled density of structural defects
Low specific density
High thermal shock resistance
High thermal insulating properties
High thermal stability
Low (or high) coefficient of friction
High resistance to wear and creep
High resistance to oxidation and corrosion
Adequate surface topography

SOURCE: Manfred Kaminsky, Surface Treatment Science International, Hinsdale, IL.

erties and performance in various environments are poorly understood. Coating providers tend to rely on experience gained empirically. Work is in progress to establish these relationships for certain processes, e.g., ion beam- or plasma-assisted physical vapor deposition. In addition, improved deposition processes are required, particularly for the coating of large components or those having a complex shape. In view of the current widespread use of coated machinery components and projected future requirements for components with advanced ceramic coatings, research in processing science for ceramic coatings remains an important priority.

Chemically Bonded Ceramics

Hardened cement pastes and concretes fall in the category of chemically bonded ceramics (CBCs) because they are consolidated through chemical reactions at ambient temperatures rather than through densification at high temperature. Owing to their low strength (compared with dense ceramics), concrete and other cementitious materials are not normally considered to be advanced materials. However, in recent years, new processing methods have led to significant improvements in the strength of chemically bonded ceramics, and further development will provide additional improvements.

Cements

Cements are chemically active binders that may be mixed with inert fillers such as sand or gravel to form concrete. Cement pastes containing minor additives such as organic polymers can also be used as structural materials. By far the most common cement used in making CBCs is portland cement. Portland and related cements are hydraulic; that is, they react with water to form a relatively insoluble aggregate. In hydraulic cements, excess water is usually added to improve the working characteristics, but this causes the hardened structures to be porous (the minimum porosity of fully-hydrated cements is about 28 percent) and of low strength.[10]

Recently, workability of such cements has been improved by using a high-shear processing technique together with pressing or rolling to remove pores from a low-water calcium aluminate cement paste containing 5 to 7 percent (by weight) organic polymers. The dense paste, which is

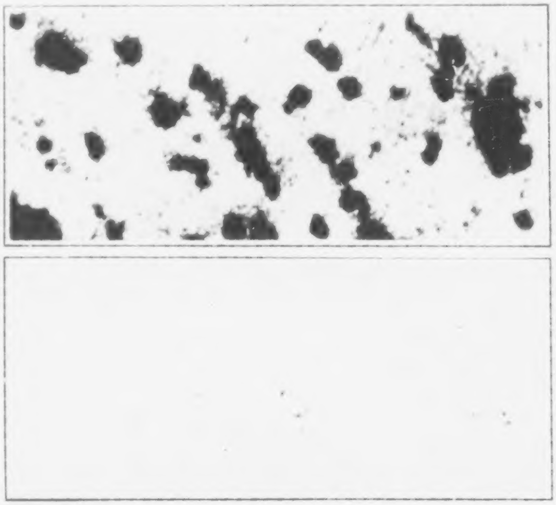

Photo credits: Imperial Chemical Industries PLC

Top photo: Conventional Portland cement paste microstructure, showing large flaws (pores).
Bottom photo: Advanced cement paste microstructure, illustrating the absence of large pores (magnification x100).

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[10] Richard A. Helmuth, Portland Cement Association, personal communication, August 1986.

sometimes called macro-defect-free (MDF) cement, has the consistency of cold modeling clay, and can be molded or extruded by techniques similar to those used for plastics.

The hardened cement paste has a compressive strength approaching that of aluminum (table 2-7) and much lower permeability than ordinary portland cement paste.[11] Although MDF cement pastes cost 20 to 30 cents per pound (compared with 3 cents per pound for portland cement paste), they are still significantly cheaper than metals and plastics.

The processing of hydraulic CBCs is very cheap because it involves only adding water, mixing, casting or molding, and permitting the material to set at room temperature or slightly elevated temperature. Very little dimensional change occurs during the set and cure, so that parts can be made to net shape. Due to the low processing temperature, it is possible to use any of a wide variety of reinforcing fibers, including metal fibers. However, the presence of organics makes them unsuitable for use above 200° F (93° C). Further work is needed to improve the long-term stability of these materials.

Photo credit: CEMCOM Research Associates, Inc.

This tool, made from a cement-based composite, is used for autoclave forming of a fiber-epoxy jet engine component.

Concrete

As chemical additives, such as organic polymers, have improved the properties of cement pastes, chemical and mineral additives have had a similar effect on concrete. Minerals such as fly ash and microscopic silica particles help to fill in the pores in the concrete and actually improve the bonding in the cementitious portion. This results in greater strength and reduced permeability.[12] In a recently developed concrete, molten sulfur is used as a binder in place of cement. Sulfur concrete has superior corrosion resistance in acidic environments and can be recycled by remelting and recasting without loss of the mechanical properties.[13]

The compressive strength of typical concretes today is around 5,000 psi (34 MPa), although concretes with strengths of 10,000 to 15,000 psi (69 to 103 MPa) are becoming common. Under laboratory conditions, compressive strengths of at least 45,000 psi (310 MPa) have been achieved, and there is no indication that the ultimate strength is being approached.[14] In concrete high-

Table 2-7.—Comparison of the Mechanical Properties of Various Cements and Aluminum

Material	Density (g/cm^3)	Flexural strength (psi)[a]	Compressive strength (psi)	Fracture energy (J/m^2)
Portland cement paste	1.6-2.0[b]	725-1,450	4,000-5,000[b]	20
Cement/asbestos	2.3	5,075	—	300
Advanced cements[c]	2.3-2.5	14,500-21,750	22,000-36,000	300-1,000
Aluminum	2.7	21,750-58,000	42,000	10,000

[a] 1 MPa = 145 psi.
[b] According to information supplied by the Portland Cement Association.
[c] The advanced cement has the following composition: 100 parts high alumina cement; 7 parts hydrolyzed polyvinylacetate; 10-12 parts water.
SOURCE: Imperial Chemical Industries.

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[11] According to product literature supplied by Imperial Chemical Industries, "New Inorganic Materials."

[12] For a recent review, see Jan Skalny and Lawrence R. Roberts, "High Strength Concrete," *Annual Review of Materials Science* 17:35, 1987.

[13] U.S. Department of Interior, Bureau of Mines, Bulletin 678, "Sulfur Construction Materials," by W.C. McBee, T.A. Sullivan, and H.L. Fike, 1985.

[14] Sidney Mindess, "Relationships Between Strength and Microstructure for Cement-Based Materials: An Overview," *Materials Research Society Symposium Proceedings* 42:53, 1985.

rise buildings, the higher compressive strengths permit use of smaller columns, with consequent savings in space and materials.

Two deficiencies in concrete as a structural material are its low tensile strength and low toughness. A typical concrete has a tensile strength below 1,000 psi (7 MPa). Steel reinforcement bars are added to the concrete to provide tensile strength. In prestressed concrete, high-strength steel wires under tension are used to keep the concrete in a state of compression. To improve strength and toughness, a variety of reinforcing fibers, including steel, glass, and polymers, have been tried, with varying degrees of success.[15] Compared with unreinforced materials, fiber reinforcement can increase the flexural strength by a factor of 2.5 and the toughness by a factor of 5 to 10.[16] This reinforcement technology, which dates back to the straw-reinforced brick of the ancient Egyptians, requires fiber concentrations that are sufficiently low (usually 2 to 5 percent by volume) to preserve the flow characteristics of the concrete, plus a chemically stable interface between the fiber and the concrete over time. Asbestos fibers served this function for many years; however, because of the health hazards, new fibers are now being sought.

In recent years, several Japanese firms have developed concretes reinforced with carbon and aramid fibers, and pitch-based carbon fiber-reinforced concrete curtain walls have been used in Tokyo office buildings. Although the carbon fiber concrete panels cost 40 percent more than precast concrete, their light weight permits the use of a lighter weight structural steel frame, resulting in overall construction cost savings.[17]

Nondestructive Evaluation

Nondestructive evaluation (NDE), which is a means of determining properties of a structure without altering it in any way, has long been used for flaw detection in ceramic materials to improve the reliability of the final product. In the future, NDE will be used for defect screening, material characterization, in-process control, and life-cycle monitoring. It will be applied to the starting materials, during the process, and to the final product.

A key goal will be the evolution of NDE techniques amenable to automation and computerization for feedback control. Powder and green body characterization will be critical for materials processed from powders. For in-process characterization, it will be essential to determine the relation between measurable quantities, obtained through the use of contact or noncontact sensors, and the desired properties. This will require developments in sensor technology as well as theories that can quantitatively relate the measured NDE signal to the specific properties of interest.

In the past, a great deal of emphasis has been placed on the sensitivity of an NDE technique, that is, the size of the smallest detectable flaw. However, experience has shown that most quality problems result not from minute flaws but from relatively gross undetected flaws introduced during the fabrication process.[18] Therefore, a more relevant criterion for reliability purposes is perhaps the size of the largest flaw that can go undetected. To date, though, there has been very little emphasis on the reliability of NDE techniques, that is, the probability of detecting flaws of various sizes.

Cost-of-production estimates for high-performance ceramic components typically cite inspection costs as accounting for approximately 50 percent of the manufacturing cost.[19] Successful NDE techniques for ceramic components, therefore, should meet two major criteria. First, they should reliably detect gross fabrication flaws to ensure that the material quality of the component is equal to that of test specimens. Second, they should be able to evaluate the quality of a complex-shaped component in a practical manner. No single NDE technique for ceramics completely satisfies these criteria. However, those that could be cost-effective for production-level inspections are identified in table 2-8.

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[15] Ibid.

[16] American Concrete Institute, "State-of-the-Art Report on Fiber Reinforced Concrete," Report No. ACI 544.1R-82, 1982.

[17] Engineering News Record, Aug. 1, 1985, p. 16.

[18] R. Nathan Katz and Alfred L. Broz, "Nondestructive Evaluation Considerations for Ceramics and Ceramic Matrix Composites," a contractor report prepared for the Office of Technology Assessment, November 1985.

[19] Ibid.

Table 2-8.—Comparison of Some Possible Production-Level NDE Techniques for Structural Ceramics

NDE technique	Detected flaw type	Sensitivity	Adaptability to complex shapes	Extent of development required for commercialization
Visual (remote)	surface	fair	good	none
Dye penetrant	surface	good	good	none
Radiographic	bulk	1-2% of specimen thickness	excellent	none
Ultrasonic	bulk and surface	good	poor	some
Holographic	surface	good	fair	large
Thermographic	surface	poor	excellent	some
Proof test	any	good, but may introduce flaws	excellent	none

SOURCE: Office of Technology Assessment, 1988.

HEALTH AND SAFETY

The most serious health hazard involved with ceramics appears to stem from use of ceramic fibers and whiskers. Studies carried out at the National Cancer Institute have indicated that virtually all durable mineral fibers having a diameter of less than 1 micrometer are carcinogenic when introduced into the lining of the lungs of laboratory rats.[20] The carcinogenicity drops with increasing diameter, such that fibers having diameters greater than 3 micrometers do not produce tumors. Recent studies on commercially available aluminosilicate fibers suggest that animals exposed to the fibers develop an increased number of lung cancers over time compared with a control group.[21]

No data on the effects of ceramic fibers or whiskers on humans are available, and no industry standards for allowable fiber and whisker concentrations in the workplace have been established. Until such data become available, the animal studies suggest that these fibers should be considered carcinogenic, and they should be treated in a manner similar to asbestos fibers.

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[20] Mearl F. Stanton, et al., *Journal of the National Cancer Institute* 67:965-75, 1981.

[21] Philip J. Landrigan, M.D., The Mount Sinai Medical Center, personal communication, August 1986.

APPLICATIONS OF STRUCTURAL CERAMICS

Figure 2-2 shows an estimated timetable for the introduction of ceramic products in various categories. It shows that some advanced structural ceramics are in production, some have near-term potential for production, and some are far from production.

Current Applications

In the United States, ceramics such as alumina and silicon carbide are already well established in commercial production for many structural applications in the categories of wear parts, cutting tools, bearings, membranes, filters, and coatings. The ceramics portion of these markets is currently small (generally less than 5 percent).[22] However, substantial growth in ceramics production is expected to occur over the next 25 years in response to increasing overall market demand, increase in the ceramics market share, and spin-off applications.

Current U.S. military applications for ceramics include radomes, armor, and infrared windows (see section entitled, *Military Applications and Production*). In Japan, ceramics are in limited production in discrete automotive engine compo-

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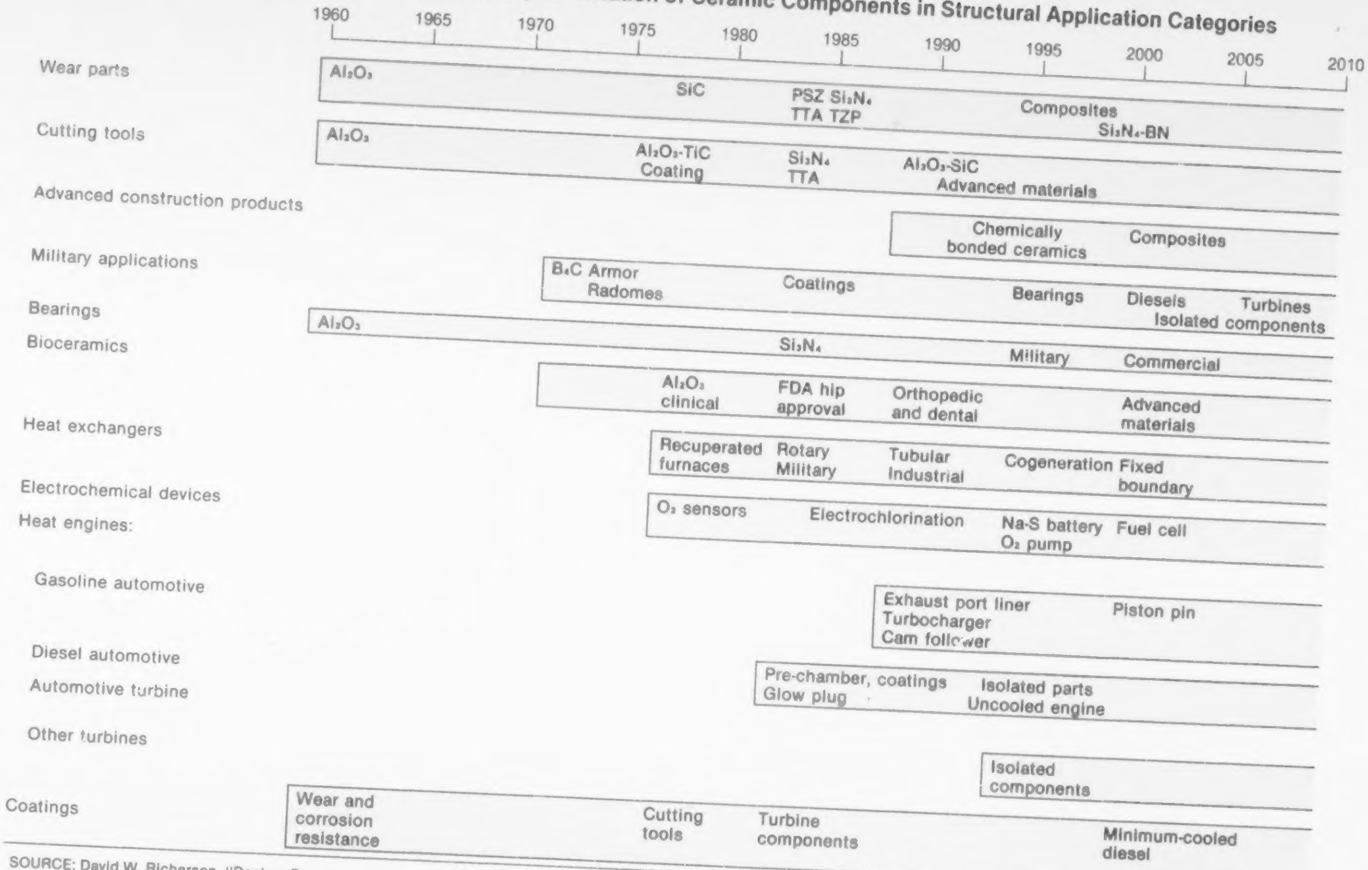
[22] U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry* (Washington, DC: U.S. Government Printing Office, March 1984), pp. 38-39.

Figure 2-2.—Estimated Scenario for Implementation of Ceramic Components in Structural Application Categories



SOURCE: David W. Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985.

nents such as turbocharger rotors, glow plugs, and precombustion chambers for diesel engines. In West Germany, the automobile manufacturer Porsche uses ceramic exhaust port liners on one model. To gain experience in fabricating advanced ceramics, Japanese firms use advanced manufacturing techniques to produce such consumer products as ceramic ballpoint pen tips, tools, and scissors. These products also help to promote familiarity with the new materials among the Japanese public.

In the United States, research funding for known near-term markets is currently being provided by industry. Much of the funding is directed toward development of new or improved ceramic or CMC materials. Key objectives are to achieve improved toughness, higher reliability, and lower cost. Development of silicon nitride, transformation-toughened ceramics, and composites has yielded materials with enhanced toughness and reliability, but costs are still high and reliability remains a problem. Currently, progress is being made in resolving these limitations, and forecasts indicate there will be large increases in the market share for ceramics.

Near-Term Applications

U.S. production in the near term (the next 10 to 15 years) is projected in advanced construction products, bearings, membranes for food processing applications, bioceramics, heat exchangers, electrochemical devices, isolated components for internal combustion engines, and military applications. The technology feasibility for these applications has generally been demonstrated, but scale-up, cost reduction, or design optimization are required.

Although much of the feasibility demonstration has occurred in the United States, foreign industry and government/industry teams, particularly in Japan, have more aggressive programs to commercialize the near-term applications. Large markets are at stake; foreign dominance of these markets would adversely affect the U.S. balance of trade.

Far-Term Applications

Some potential applications of ceramics require solution of major technical and economic problems. These high-risk categories are categorized as far-term (greater than 15 years away). The ultimate payoff may be large, but it is not possible to predict confidently that the problems will be overcome to achieve the benefits.

Far-term applications include the automotive gas turbine engine, the advanced diesel, some electrochemical devices such as fuel cells, some heat exchangers, and some bearings. A variety of other turbines, especially those for aircraft propulsion and utility-scale power generation, should also be categorized as far-term.

Substantial design, material property, and manufacturing advances are necessary to achieve production of applications in the far-term category. In general, risk is perceived by industry to be too high and too long-range to justify funding the needed developments. Advancement will likely be driven by government funding. In many of these categories, military use will predate commercial use.

Markets for Advanced Structural Ceramics

Estimated structural ceramics markets in the year 2000 for several of the categories listed above are shown in figure 2-3.

Wear Parts

Wear parts include such applications as seals, valves, nozzles, wear pads, grinding wheels, and liners. The Department of Commerce has estimated that by the year 2000 ceramics could capture roughly 6 percent of the wear-parts market, which is currently dominated by tungsten carbide, cermets, and specialty steels. With the total market estimated at $9 billion, the ceramic portion would be $540 million.[23]

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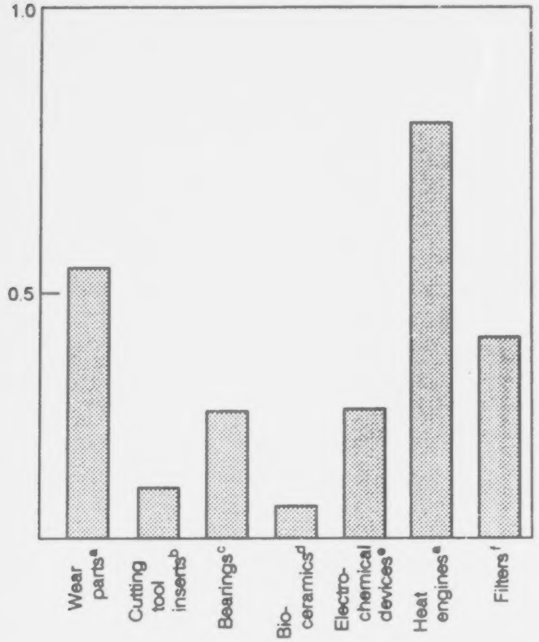
[23] Ibid., p. 35.

Figure 2-3.—Projected U.S. Markets for Structural Ceramics in the Year 2000 (billions of dollars)



SOURCES: [a] U S Department of Commerce, "A Competitive Assessment of the U S Advanced Ceramics Industry" (Washington, DC, U S Government Printing Office, March 1984)

[b] E P Rothman, J Clark, and H K Bowen, "Ceramic Cutting Tools: A Production Cost Model and an Analysis of Potential Demand," Advanced Ceramic Materials, American Ceramics Society, Vol I, No 4, October, 1986, pp 325-331

[c] *High Technology*, March 1986, p 14

[d] Business Communications Co , Inc , as reported in *Ceramic Industry*, Jan 1988, p 10

[e] David W Richerson, "Design, Processing Development, and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report prepared for the Office of Technology Assessment, December 1985

[f] Assumes a doubling from 1986 Paul Hurley, "New Filters Can Clean Up in New Markets," High Technology, August 1987

Cutting Tools

Ceramics have demonstrated capability as cutting tools, especially in competition with tungsten carbide-cobalt cermets as inserts for metal turning and milling operations. The advantage of ceramics compared with carbides is retention of high hardness, strength, and chemical inertness to temperatures in excess of 1000° C (1832° F). This permits use of the ceramics at much higher machining speeds than can be tolerated by carbides.

However, the ceramics have lower toughness than the carbide materials, and have only been used successfully in the limited operations of turning and milling. A further impediment to the use of ceramics, especially in the United States, has been equipment limitations; much of the production metal machining equipment does not have the rigidity or speed capability to use ceramics.

A 1986 projection for ceramic and ceramic-coated cutting tools (the largest portion of which are inserts) places the growth rate at about 6 percent per year from a present market of $600 million to a market of over $1 billion by 1995.[24] The vast majority of this market is coated carbide tooling. A second projection, for only the solid ceramic insert cutting tool market, is $128 million overall market by the year 2000.[25]

Bearings

High-performance ceramic bearings have been developed for military applications such as missiles. The primary candidate material is hot pressed silicon nitride. Ceramics offer resistance to low-temperature corrosion, high-temperature stability, low density, and the ability to operate for a moderate length of time with little or no lubrication. Hot isostatic pressing is being developed to improve properties and to decrease cost by permitting near-net-shape fabrication.

The military developments will yield a technology base that can be applied to commercial products such as instrumentation bearings, hydraulic and pneumatic activator systems, and ceramic coatings on the foils in gas bearings. Potential ceramic bearing markets have been estimated to be $300 million per year.[26]

Membranes

Membrane filters are used in a wide variety of separation and purification processes, and markets are projected to increase from $500 million in 1986 to $2 billion by 1995. Some of the fastest growing segments are expected to be food and

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[24] G. Shro[illegible] [illegible]I International, "Business Opportunities in Advanced Structural Ceramics and Ceramic Coatings," excerpted in *Advanced Ceramic Materials* 1(4):294, October 1986.

[25] Elaine P. Rothman, Joel Clark, and H. Kent Bowen, "Ceramic Cutting Tools: A Production Cost Model and an Analysis of Potential Demand," *Advanced Ceramic Materials*, American Ceramic Society 1(4):325-331, October 1986.

[26] *High Technology*, March 1986, p. 14.

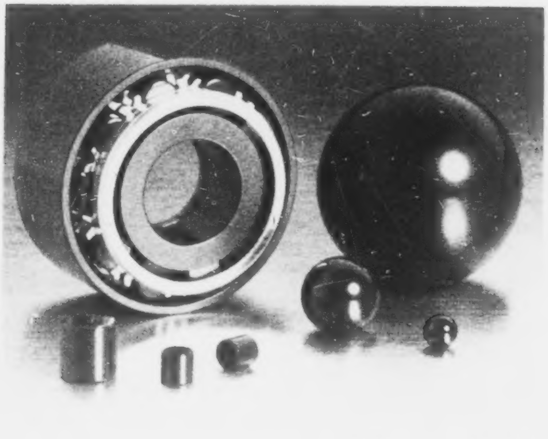

Photo credit: Norton Co

Silicon nitride anti-friction bearing components offer improved wear resistance and fatigue life compared to most bearing steel.

beverage processing, aqueous waste processing, diesel engine exhaust filters, and gas separation. Although ceramic membranes cost more than the more well-established polymer membranes, ceramics offer a number of performance advantages, including resistance to high temperatures, chemical and mechanical stability, and ease of cleaning. In 1986, markets for ceramic membranes were estimated at $200 million, and growth rates of up to 30 percent are projected into the 1990s.[27]

Coatings

Ceramic coatings should be considered an extremely important technology for extending the performance of metal components, and, in some cases, they may be an excellent alternative to monolithic ceramics. They provide a variety of benefits, including abrasion resistance, thermal protection, corrosion resistance, and high-temperature lubrication. Applications include ultrahard coatings for cutting tools, thermal insulation and lubricating coatings for adiabatic diesel engines and cooled gas turbines, and bioactive glass coatings for metal orthopedic implants. The list could be expanded to include other sectors such as mining (e.g., drills); utilities (e.g., turbine-generator sets, heat exchangers); agriculture (e.g., plows and tillers); and aerospace (e.g., bearings, power transfer assemblies, and actuator drive systems).

The availability of advanced ceramic coatings is expected to be a significant benefit to the U.S. economy. The value of the market for ceramic coatings is not easily assessed because the range of applications is so wide. In 1985, markets for ceramic coating materials were estimated at $1 billion worldwide, of which about 60 to 70 percent was domestic.[28] This estimated market includes jet engine, printing, chemical, textile, and tool and die applications. This list could be greatly expanded in the future to include wear parts, bearings, biomaterials, heat exchangers, and automotive components.

Advanced Construction Products

Potential applications of advanced cement-based materials include floors, wall panels, and roof tiles, in addition to pipes, electrical fittings, and cabinets. The cements can be laminated with wood or foam to form hard, decorative, and protective surfaces.[29] Advanced cement pastes cost $0.20 to $0.30 per pound (compared with $0.75 to $2 per pound for metals and plastics), and they could displace these materials in the future in many common uses.

The development of a cost-effective, durable, high-tensile, and high-compressive strength concrete would have dramatic implications for the infrastructure of the United States. It has been estimated that between 1981 and the end of the century, the Nation will spend about $400 billion on replacement and repair of pavements and about $103 billion to correct bridge deficiencies.[30] Cost savings of about $600 million per year could result from implementing new technologies.[31]

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[27] Paul Hurley, "New Filters Clean Up in New Markets," *High Technology*, August 1987.

[28] Julie M. Schoenung, Elaine P. Rothman, and Joel P. Clark, "Properties, Costs and Applications of Ceramics and Ceramic Matrix Composites," a contractor report prepared for the Office of Technology Assessment, December 1985.

[29] Imperial Chemical Industries, "New Inorganic Materials" (product literature).

[30] National Research Council, Transportation Research Board, *America's Highways: Accelerating the Search for Innovation*, special report No. 202, 1984.

[31] Ibid.

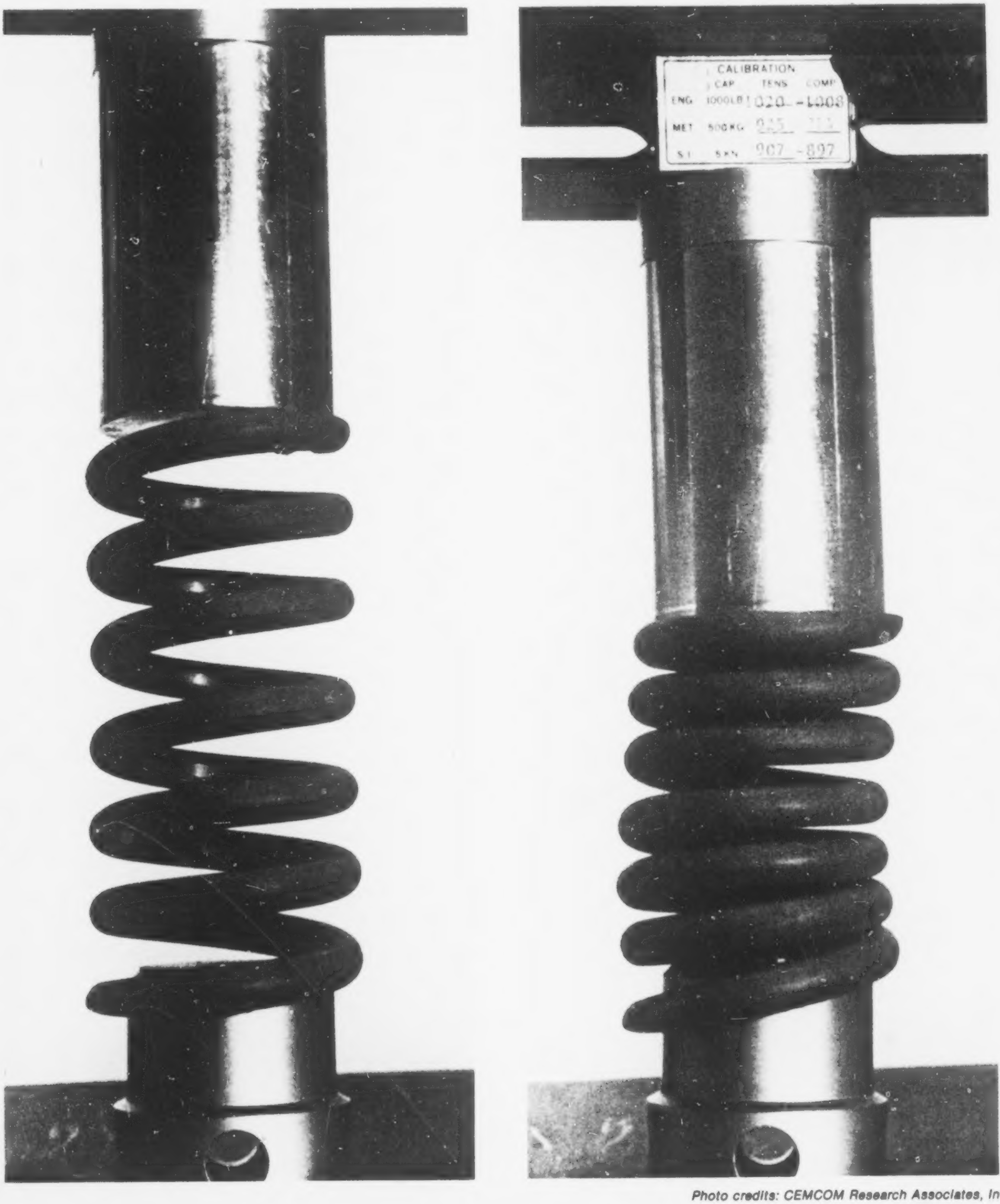
CALIBRATION
CAP
TENS
COMP
ENG
1000LB
1020
-1008
MET
500KG
S.I.
5KN
907
-897

Photo credits: CEMCOM Research Associates, Inc.

A spring made from a high-strength cement, formed by extrusion processing. Left: natural length. Right: compressed. The spring is not intended for any practical use, but demonstrates the versatility and resilience of the material.

In addition to reducing repair and maintenance costs, new materials would provide other benefits. For instance, high compressive strength concrete can be used to reduce the number and thickness of concrete bridge girders, significantly reducing the structural weight.[32] In concrete highrise buildings, the use of such materials permits a reduction in the diameter of the columns, thus freeing up additional floor space.

There are major barriers to the development and implementation of new technologies in the construction industry. Some of those most often cited are industry fragmentation (e.g., some 23,000 Federal, State, and local agencies operate the Nation's highway system); an arrangement that awards contracts to the lowest bidder; and low industry investment in research as a percentage of sales (the steel industry, by contrast, invests eight times more).[33] The low investment is due in part to the fact that the principal benefits of the use of better materials accrue to the owner of the highway or bridge (the taxpayer) rather than to the cement producer.[34]

The Surface Transportation Assistance Act of 1986 (Public Law 100-17) sets aside 0.25 percent of Federal aid highway funds for the 5-year, $150 million Strategic Highway Research Program. The program, which is administered by the National Research Council, has targeted six priority research areas for support: asphalt characteristics, $50 million; long-term pavement performance, $50 million; maintenance cost-effectiveness, $20 million; concrete bridge components, $10 million; cement and concrete, $12 million; and snow and ice control, $8 million.[35]

Bioceramics

Bioceramics, or ceramics for medical applications such as dental or orthopedic implants, represent a major market opportunity for ceramics in the future. The overall worldwide market for biocompatible materials is currently about $3 billion, and this is expected to double or triple in the next decade.[36] Ceramics could account for 25 to 30 percent of this market.[37] However, not all estimates are so optimistic. One projection places the U.S. bioceramics market at $8 million in 1987, increasing to $60 million by 2000.[38]

Bioceramics may be grouped into three categories: nearly inert, surface-active, and resorbable.[39] Nearly inert ceramics can be implanted in the body without toxic reactions. These materials include silicon nitride-based ceramics, transformation-toughened zirconia, and transformation-toughened alumina.

Surface-active ceramics form a chemical bond with surrounding tissue and encourage ingrowth. They permit the implant to be held firmly in place and help prevent rejection due to dislocation or to influx of bacteria. Surface-active ceramics that will bond to bone include dense hydroxyapatite, surface-active glass, glass-ceramic, and surface-active composites. The function of resorbable bioceramics is to provide a temporary space filler or scaffold that will serve until the body can gradually replace it.

Resorbable ceramics are used to treat maxillofacial defects, for filling periodontal pockets, as artificial tendons, as composite bone plates, and for filling spaces between vertebrae, in bone, above alveolar ridges, or between missing teeth. An early resorbable ceramic was plaster of paris (calcium sulfate), but it has been replaced by trisodium phosphate, calcium phosphate salts, and polylactic acid/carbon composites.[40]

Any new material intended for use in the human body must undergo extensive testing before it is approved. Preclinical testing, clinical studies, and followup generally take a minimum of 5 years to complete.[41] However, ceramics have been in

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[32] J.E. Carpenter, "Applications of High Strength Concrete for Highway Bridges," *Public Roads* 44(76), 1980.

[33] National Research Council, op. cit., 1984.

[34] Ibid.

[35] "Construction and Materials Research and Development for the Nation's Public Works," OTA staff paper, June 1987.

[36] Larry L. Hench and June Wilson Hench, "Biocompatibility of Silicates for Medical Use," *Silicon Biochemistry*, CIBA Foundation Symposium, No. 121 (Chichester, England: John Wiley & Sons, 1986), pp. 231-246.

[37] Larry L. Hench, University of Florida, personal communication, August 1986.

[38] According to Business Communications Co., Inc., as reported in *Ceramic Industry*, January 1988, p. 10.

[39] J.W. Boretos, "Ceramics in Clinical Care," *American Ceramics Society Bulletin* 64(8):630-636, 1985.

[40] Ibid.

[41] Edwardo March, Food and Drug Administration, personal communication, August 1986.

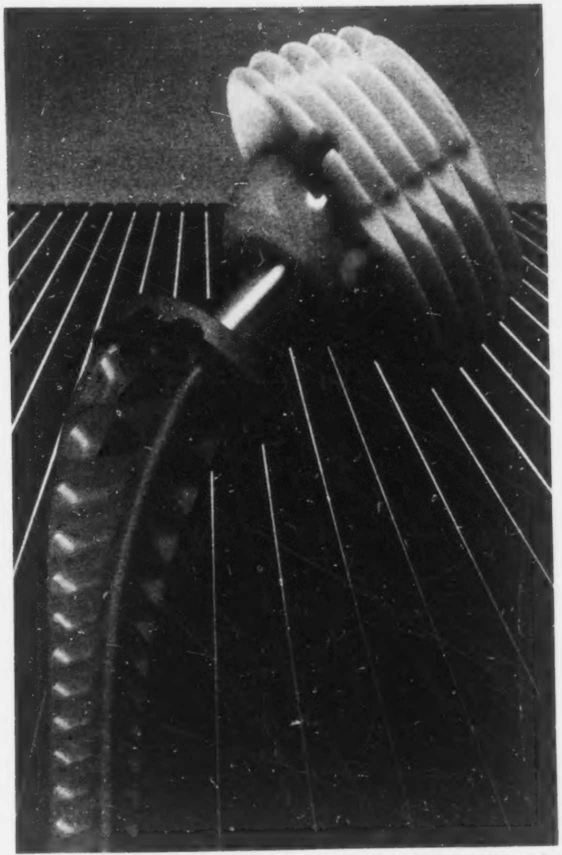

Photo credit: Richards Medical Co

Total hip system including ceramic femoral head and acetabular cup, with metal femoral stem. The system is manufactured in West Germany and marketed by Richards Medical Co.

clinical use for some 15 years, and are gaining acceptance. Industry interest in bioceramics has increased since 1980; however, no data are currently available on aggregate R&D spending either by industry or by the Federal Government. In contrast, France, West Germany, and especially Japan have aggressive programs of government support for the commercialization of bioceramics.[42] All researchers interviewed by OTA agreed that the Japanese effort in bioceramics is considerably larger than the U.S. effort.

Heat Exchangers

Ceramic heat exchangers are cost-effective because they can use waste heat to reduce fuel consumption. Heat recovered from the exhaust of a furnace is used to preheat the inlet combustion air so that additional fuel is not required for this purpose. The higher the operating temperature, the greater the benefit. Ceramic systems have the potential to reduce fuel consumption by more than 60 percent.[43]

Ceramic heat exchangers may be used in a variety of settings, including industrial furnaces, industrial cogeneration, gas turbine engines, and fluidized bed combustion. The size of the unit, manufacturing technique, and material all vary depending on the specific application. Sintered silicon carbide and various aluminosilicates have been used in low-pressure heat exchangers because of their thermal shock resistance; however, the service temperature of these materials is currently limited to under 2200° F (1204° C). Silicon carbide is being evaluated for higher temperatures, but considerable design modifications will be necessary.[44]

Federal Government support has been necessary to accelerate development of the ceramic materials and system technology for heat exchangers, in spite of the design projections of significant fuel savings and short payback time. The material manufacturers, system designers, and end users have all considered the risks too high to invest their own funds in the development and implementation of a system.

Three of their specific concerns are: 1) the high installed cost (up to $500,000 for a unit that delivers 20 million British thermal units per hour), which represents a significant financial risk to the user for a technology that is not well proven; 2) many potential end users are in segments of industry that presently are depressed; and 3) designs vary according to each installation, leading the user to want a demonstration relevant to his particular situation.

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[42] Richerson, op. cit., footnote 4.

[43] S.M. Johnson and D.J. Rowcliffe, SRI International Report to EPRI, "Ceramics for Electric Power-Generating Systems," January 1986.

[44] Richerson, op. cit., footnote 4.

Many of the ceramic heat exchanger programs were initiated in the 1970s when there was a national sense of urgency concerning the energy crisis. In recent years, declining fuel prices have generally reduced this sense of urgency. As long as low fuel prices persist, this could delay the widespread implementation of ceramic heat exchangers for waste heat recovery.

Electrochemical Devices

Although not strictly structural applications of ceramics, devices in this category use ceramics for both their electrical and structural properties. Typically, the ceramic, such as zirconia or beta alumina, serves as a solid phase conductor for ions such as oxygen or sodium. Examples include oxygen sensors, oxygen concentration cells, solid oxide fuel cells, the sodium-sulfur battery, sodium heat engine, and electrodes for metal winning and electrochlorination cells. As a group, these applications could comprise a market of over $250 million for ceramics by the year 2000.[45]

Heat Engines

The advantages of using ceramics in advanced heat engines have been widely publicized. These include increased fuel efficiency due to higher engine operating temperatures, more compact designs, and reduction or elimination of the cooling system.[46] Ceramics are being considered in three general categories: 1) discrete components such as turbocharger rotors in metal reciprocating engines; 2) coatings and monolithic hot-section components in advanced diesel designs; and 3) all-ceramic gas turbine engines.

Some analysts have predicted that components for heat engines will be the largest area of growth for structural ceramics over the next 25 years. Projected market estimates vary widely. Earlier estimates tended to be more optimistic, with several analysts projecting U.S. ceramic heat engine markets around $5 billion by the year 2000. The Department of Commerce has conservatively estimated a U.S. market of $56 million by 1990 and $840 million by 2000.[47] A study by Charles River Associates estimates U.S. consumption of ceramic heat engine parts at $25 to $45 million in 1990 and $920 million to $1.3 billion by 2000.[48]

Some structural ceramic components are already in limited production in automobile engines. Ceramic precombustion chambers and glow plugs for diesels, as well as ceramic turbocharger rotors, are now in production in current model Japanese cars.

Ceramic engine components markets will grow, but not to a level that will account for the projected $1 billion sales for heat engine components in the year 2000. Growth to this level would require material and design technology breakthroughs, as well as manufacturing scale-up and cost reduction. In view of these technical and economic barriers, the more conservative estimates are likely to be the more accurate.

Gasoline Engines

The automotive internal combustion gasoline engine offers a vast market for materials. Total sales for 1985 of cars and trucks in the free world have been estimated at 38.7 million units.[49] Any part replacement or new part would represent a volume market with substantial sales, even if the unit price were small. However, current engine designs are considered by automotive companies to be mature, reliable, and cost-effective.

Very few incentives for change exist. Cost reduction does remain a significant incentive, but this goal is extremely difficult to satisfy for a new material, whose introduction may require redesign of adjacent parts, retooling, and modification of the production line.

Another incentive is to develop a new technology that may be applicable to advanced designs. This would involve both generic and directed R&D, with the primary objective of maintaining a competitive position. Ceramics within this category that have potential for production in-

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[45] Ibid.

[46] R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," *Materials Science and Engineering* 71:227-249, 1985.

[47] U.S. Department of Commerce, op. cit., footnote 22.

[48] Charles River Associates report prepared for the National Bureau of Standards, "Technological and Economic Assessment of Advanced Ceramic Materials, Vol. 2: A Case Study of Ceramics in Heat Engine Applications," NBS-GCR 84-4760-2, August 1984.

[49] Richerson, op. cit., footnote 4.

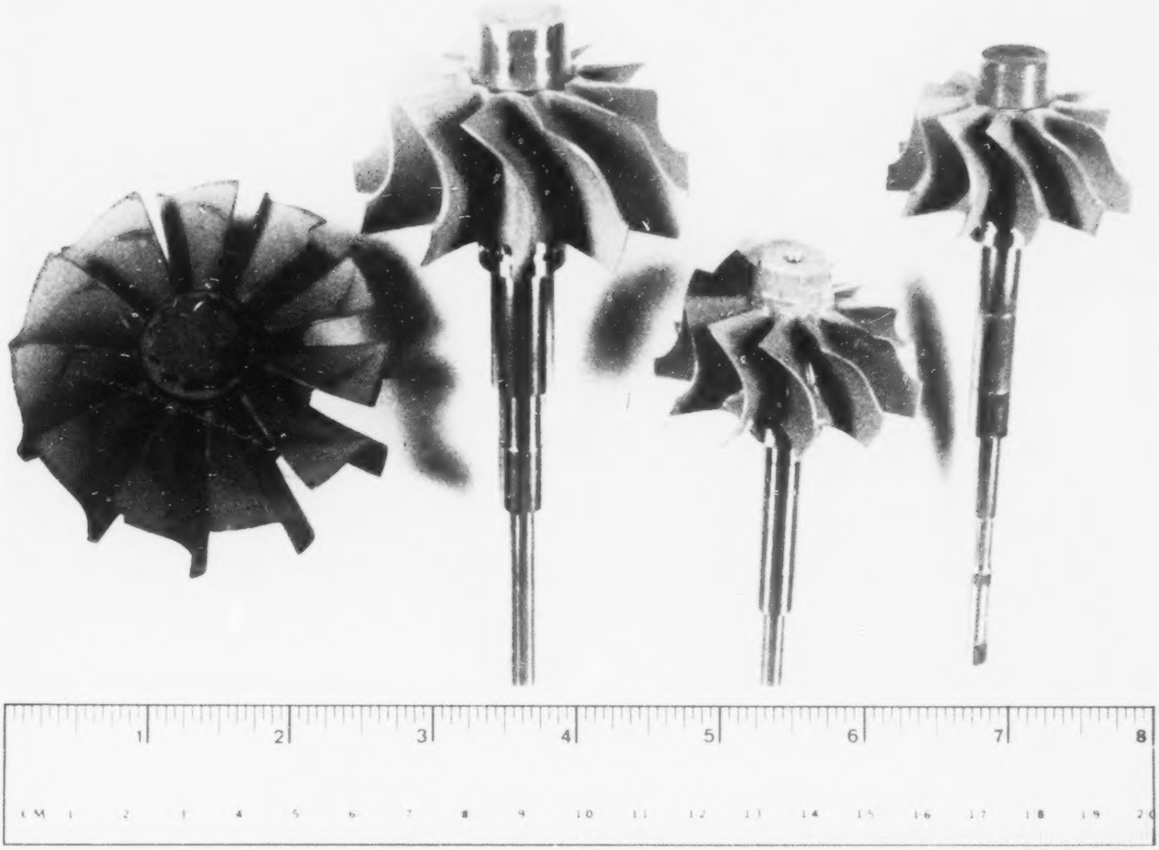

Photo credit: The Garrett Corp.

Ceramic turbocharger turbine rotors

clude exhaust port liners, cam followers, and turbocharger components. To date, U.S. firms have not introduced these products, although R&D programs continue.

The United States remains behind Japan in procuring the advanced production equipment needed to produce ceramic turbocharger rotors. U.S. automotive companies do not appear to have the same level of confidence as the Japanese that a ceramic turbocharger rotor market will develop. In spite of this, U.S. industry is still funding considerable R&D on ceramic turbocharger rotors. One study has estimated that if a ceramic rotor price of $15 can be reached and if performance and reliability are acceptable, a worldwide market of $60 million could be generated for ceramic turbocharger rotors by the year 2000.[50]

The ceramic turbocharger rotor has a significance far beyond its contribution to the performance of the engine. It is regarded as a forerunner technology to far more ambitious ceramic engines, such as the advanced gas turbine. Design, fabrication, and testing methods developed for the turbocharger rotor are expected to serve as a pattern for subsequent ceramic engine technology efforts.

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[50] Elaine P. Rothman, "Advanced Structural Ceramics: Technical/Economic Process Modeling of Production and a Demand Analysis for Cutting Tools and Turbochargers," Materials Systems Laboratory, Massachusetts Institute of Technology, August 1985.

Diesel Engines

There are several levels at which ceramics could be incorporated in diesel engines, as shown in table 2-9. The first level involves a baseline diesel containing a ceramic turbocharger rotor and discrete ceramic components. The second level adds a ceramic cylinder and piston, and eliminates the cooling system. The ceramic used at this level would provide high-temperature strength, rather than thermal insulation.

The third level would use ceramics for thermal insulation in the hot section as well as in the exhaust train. Turbocompounding would be used to recycle energy from the hot exhaust gases to the drive train. The fourth level would use advanced minimum friction technology to improve the performance of the engine. Appropriate aspects of this technology also could be used at levels one, two, or three.

The four levels place different demands on the ceramic materials. Levels one and two require a low-cost, high-strength material, but without insulating properties; sintered silicon nitride or silicon carbide would be possibilities here. It has been suggested that level two represents the best compromise for light-duty ceramic diesels such as those in automobiles.[51] Level three would require an insulating ceramic, probably zirconia or a zirconia-based composite. Level three is the level at which the most significant improvements in fuel efficiency would be realized. However, the current zirconia and alumina-zirconia transformation-toughened ceramics are not reliable at the high stress of the piston cap and do not have a low enough coefficient of friction to withstand the sliding contact stress of the rings against the cylinder liner. These materials do seem to have adequate properties, however, for other components such as the head plate, valve seats, and valve guides.[52]

Emission requirements will likely affect the size of the diesel market for passenger cars and trucks. Diesel engines generally produce a high level of particulate emissions. The higher operating temperatures of the adiabatic diesel could reduce emissions or permit emission control devices to operate more efficiently. The market for ceramics could also be affected by the fact that one major candidate for diesel emission control is a ceramic particle trap. However, such a trap is likely to be expensive.

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[51] Katz, op. cit., footnote 46.

[52] Richerson, op. cit., footnote 4.

Table 2-9.—Future Diesel Engine Technology Development Scenario

Technology level	Engine configuration	Potential ceramic components	Potential payoffs
1	State-of-the-art engine, turbocharged	Turbocharger Valve train components Prechamber, glow plugs	Improved performance Reduced cost? Early manufacturing experience
2	Uncooled, non-adiabatic (no water or air cooling) (no turbo-compounding)	Turbocharger Valve train components Piston, cap Cylinders, liners	Reduced weight – efficiency gain Gives option to improve aerodynamics → efficiency gain Reduced maintenance Reduced engine systems cost? Flexibility of engine placement
3	Adiabatic turbo-compound	Turbocharger Turbo-compound wheel Valve train components Piston, cap Cylinders, liners Exhaust train insulation	Very significant reduction in specific fuel consumption Improved aerodynamics Reduced maintenance
4	Minimum friction technology (could be combined with 1, 2 or 3)	Air bearings High-temperature rings High-temperature bearings Nongalling wear surfaces Low friction liquid, lubricant-free bearings	Lower specific fuel consumption

SOURCE: R. Nathan Katz, "Applications of High Performance Ceramics in Heat Engine Design," *Materials Science and Engineering* 71:227-249, 1985.

Ceramic coatings may be an alternative to monolithic ceramics in diesel applications. Zirconia coatings can be plasma-sprayed onto metal cylinders to provide thermal insulation. In a joint program between the U.S. Army Tank Automotive Command and Cummins Engine Co., the combustion zone of a commercial Cummins NH diesel engine was coated with a zirconia-based ceramic and installed in a 5-ton Army truck, minus the cooling system. The engine accumulated over 9,375 miles (15,000 kilometers) of successful road testing.[53] The current state-of-the-art thickness of zirconia coatings is 0.03 to 0.05 inch (0.762 to 1.27 millimeter). It is estimated that thicknesses of 0.125 inch (3.175 millimeter) will be required to provide thermal insulation comparable to monolithic zirconia.[54] The coating is not as impermeable or as resistant to thermal shock as the monolithic zirconia. However, the coated metal part has greater strength and toughness than the all-ceramic part.

In the past, confusion has arisen because identical configurations of ceramic and metal engines have not been compared. It is important to separate out the configuration options, such as turbocharging, turbocompounding, heat recovery, cooling, etc., from the material options to isolate the benefits of the use of ceramics. Failure to do this has led to overestimation of the benefits of ceramics. For instance, a recent study of a ceramic diesel design funded by the Department of Energy indicates that:

> . . . a practical zirconia-coated configuration with a cooled metal liner, intercooled, with combined turbocompounding and Rankine cycle exhaust heat recovery, provides a 26 percent increase in thermal efficiency over a metallic, cooled, turbocharged, intercooled, baseline engine.[55]

However, the bulk of the performance improvement was attributed to the turbocompounding and the Rankine cycle exhaust heat recovery. Only 5.1 percent was attributed to the improved thermal insulation. Recent work at Ford Motor Co. also showed a 5- to 9-percent increase in fuel efficiency in an uncooled test engine fitted with ceramic inserts, compared to the baseline water-cooled design.[56]

Charles River Associates predicts that the uncooled ceramic diesel engine system will be the first to be commercialized.[57] It projects that the initial introduction will be in the late 1980s to early 1990s, and could account for 5 percent of new engines manufactured in 1995.

This projection is more optimistic than the above discussion would imply. Zirconia materials do not yet exist that can be used for level three technology, wherein the greatest fuel efficiencies are expected. It remains to be seen whether the elimination of the cooling system will provide sufficient incentives to U.S. automakers to commercialize level two ceramic technology.

Japan in particular has very active research programs both in material and diesel engine development. Isuzu, the strongest ceramic engine advocate of all of the Japanese auto companies, has reported more than 300 miles (480 kilometers) of road testing and is projecting 1990 production.[58] Toyota has plans to produce an all ceramic diesel, using injection molded and sintered silicon nitride by 1992. Every part will be proof tested. The largest Japanese automakers all maintain extensive research activities in the area of ceramic engines.[59]

Automotive Gas Turbines

The major incentive for using ceramics in turbines is the possibility of operating the engine at turbine inlet temperatures up to about 2500° F (1371° C), compared with superalloy designs, that are limited to about 1900° F (1038° C) without cooling. This temperature difference translates into an increased thermal efficiency from around

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[53] Katz, op. cit., footnote 46.

[54] Bill Mandler, Cummins Engine Co., personal communication, August 1986.

[55] T. Morel, et al., "Methods for Heat Transfer and Thermal Analysis of Insulated Diesels," *Proceedings of the 23rd Automotive Technology Development Contractors Coordination Meeting* (Dearborn, MI: Society of Automotive Engineers, March 1986).

[56] Arthur F. McLean, "Materials Approach to Engine/Component Design," *Ceramic Materials and Components for Engines*, W. Burk and H. Hausner (eds.) (Bad Honnef, FRG: Verlag Deutsche Keramische Gesellschaft, 1986), p. 1023.

[57] Charles Rivers Associates, op. cit., footnote 48.

[58] Richerson, op. cit., footnote 4.

[59] Robert J. Gottschall, "Basic Research in Ceramic and Semiconductor Science at Selected Japanese Laboratories," DOE/ER-0314, a Department of Energy report available from the National Technical Information Service, March 1987, p. 39.

40 percent to nearly 50 percent.[60] Power increases of 40 percent and fuel savings of around 10 percent have been demonstrated in research engines containing ceramic components.[61] Other potential advantages include reduced engine size and weight, reduced exhaust emissions, and the capability to burn alternative fuels, such as powdered coal.

Structural ceramics represent an enabling technology for the automotive gas turbine; i.e., ceramics are the key to designing and manufacturing an automotive turbine that can compete in cost or performance with current gasoline and diesel engines. Extensive design, materials, and engine efforts have been made over the past 15 years in the United States, Europe, and Japan. These efforts have resulted in significant progress in design methods for brittle materials, the properties of silicon nitride and silicon carbide, fabrication technology for larger and more complex ceramic components, NDE and proof testing, and engine assembly and testing.

Ceramic components have been operated in prototype turbine engines in West Germany, Sweden, Japan, and the United States. The tests in the United States have involved highly instrumented development engines in test cells.[62] Current programs have achieved over 100 hours of operation at temperatures above 2000° F (1093° C).[63] These achievements, although impressive, are still far from the performance required of a practical gas turbine engine, which will involve continuous operation above 2500° F (1371° C). The limiting component in these engines appears to be the rotor, which must spin at about 100,000 rpm at these temperatures. The most reliable rotors available have generally been manufactured in Japan.[64] The target automotive gas turbine engine is designed to provide about 100 horsepower with fuel efficiencies of about 43 miles per gallon for a 3,000-pound automobile.[65]

The automotive gas turbine would be a more revolutionary application of ceramics than the diesel. The diesel engine is a familiar technology and incorporation of ceramics can occur in stages, consistent with an evolutionary design. The gas turbine, on the other hand, represents a completely new design requiring completely new tooling and equipment for manufacture. Because of the remaining technical barriers to ceramic gas turbines and the fact that they represent a complete departure from current designs, it is unlikely that a ceramic gas turbine passenger car could be produced commercially before 2010.[66] In view of this long development time, it appears possible that this propulsion system could be overtaken by other technologies, including the ceramic diesel. One factor that would favor the turbine engine would be dramatically increased fuel costs. In the case that traditional fuels became scarce or expensive, the turbine's capability to burn alternative fuels could make it the powerplant of choice in the future.

In summary, the outlook for ceramic heat engines for automobiles appears to be highly uncertain. The performance advantages of ceramic engines are more apparent in the larger, more heavily loaded engines in trucks or tanks than they are in automobiles. Ceramic gas turbines and adiabatic diesel designs do not scale down in size as efficiently as reciprocating gasoline engines.[67] Thus, if the trend toward smaller automobiles continues, reciprocating gasoline engines are likely to be favored over advanced ceramic designs.

The prevailing approach of U.S. automakers—that of waiting to see if a clear market niche for ceramics develops before investing heavily in the technology—is likely to mean that previous forecasts of the U.S. ceramics heat engine market, which cluster in the $1 to $5 billion range by the

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[60] John Mason, Garrett Corp., presentation at the Society of Automotive Engineers International Congress and Exposition, Detroit, MI, February 1986.

[61] David W. Richerson and K.M. Johansen, "Ceramic Gas Turbine Engine Demonstration Program," final report, DARPA/Navy contract N00024-76-C-5352, May 1982.

[62] David W. Richerson, "Evolution in the U.S. of Ceramic Technology for Turbine Engines," *American Ceramics Society Bulletin* 64(2):282-286, 1985.

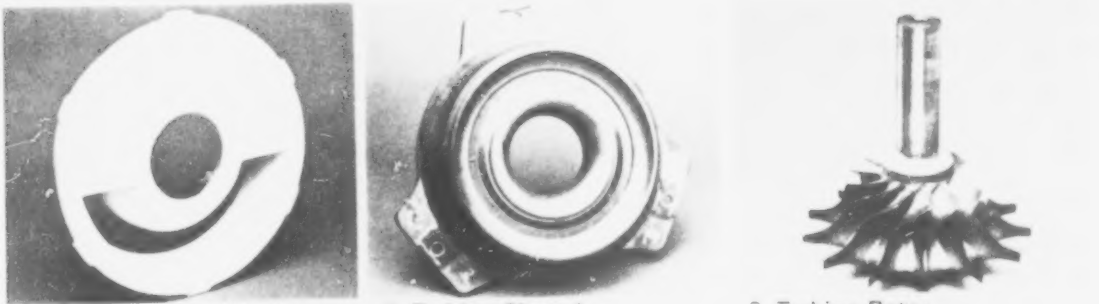
[63] Mason, op. cit.

[64] Richard Helms, General Motors Corp., presentation at the Society of Automotive Engineers International Congress and Exposition, Detroit, MI, February 1986.

[65] Katz, op. cit., footnote 46.

[66] Richerson, op. cit., footnote 4.

[67] U.S. Congress, Office of Technology Assessment, *Increased Automobile Fuel Efficiency and Synthetic Fuels: Alternatives for Reducing Oil Imports*, OTA-E-185 (Washington, DC: U.S. Government Printing Office, September 1982), p. 145.



1. Flow Separator Housing 2. Turbine Shroud 3. Turbine Rotor

4. Inner Diffuser HSG 5. Outer Diffuser HSG 6. Turbine Backshroud

7. Stator Vane Segments 8. Turbine Transition Liner 9. Combustor Baffle

10. Bolts 11. Regenerator Shield 12. Alumina-Silica Insulation

Photo credit: The Garrett Corp.

Prototype ceramic gas turbine engine components year 2000, are too optimistic. On the other hand, the Japanese approach, in which ceramics are steadily being incorporated in engines on a more experimental basis, reflects greater faith in the future of the technology. If a substantial automotive market for ceramics does develop, heat engine applications for ceramics would be one of the most highly leveraged in terms of economic benefits and jobs.[68] [69]

Military Applications and Production

Production of ceramics for military applications is projected to expand substantially during the next 25 years.[70] Near-term growth is expected for armor, radomes and infrared windows, bearings for missiles, and rocket nozzles (carbon-carbon composites and ceramic-coated carbon-carbon composites). New applications are likely to be laser mirrors, gun barrel liners, rail gun components, and turbine and diesel engine components. Ceramics and ceramic composites in many cases offer an enabling capacity that will lead to applications or performance that could not otherwise be achieved. Some of the resulting technology will be suitable for commercial spinoffs if acceptable levels of fabrication cost and quality-control cost can be attained.

Diesels

In military diesels, ceramics provide much the same benefits as in commercial diesels. Of particular interest to the military is the elimination of the cooling system to achieve smaller packaging volume and greater reliability. Considerable progress has been made through the use of ceramic coatings. Monolithic ceramics have also been tried, but have been successful only in a few components and still require further development. A military diesel with minimal cooling achieved primarily with ceramic coatings could be produced by 1991. Engines containing more extensive ceramic components are not likely to appear before about 1995 to 2000.[71]

Turbines

Turbine engines are in widespread military use for aircraft propulsion, auxiliary power units, and other applications. They are being considered for propulsion of tanks, transports, and other military vehicles. Ceramics have the potential to enable advanced turbines to achieve major improvements in performance: as much as 40 percent more power, and fuel savings of 30 to 60 percent.[72] In addition, they offer lower weight, longer range, decreased critical cross section, and decreased detectability.

Design and material technologies are available in the United States to produce high-performance ceramic-based turbine engines for short-life applications such as missiles and drones. Furthermore, it appears that these engines have potential for lower cost than current superalloy-based short-life engines.[73]

Longer-life engines will require considerable development to demonstrate adequate reliability. This development must address both design and materials in an iterative fashion. Although the use of ceramic thermal barrier coatings in metal turbines is well under way, new turbines designed specifically for ceramics are not likely to be available before the year 2000.

FUTURE TRENDS IN CERAMICS

Ceramic Matrix Composites

Major improvements in the fracture properties of ceramics have been obtained by reinforcing matrices with continuous, high-strength fibers. Optimum microstructures result in composites that do not fail catastrophically and therefore have mechanical properties that are very different from those of monolithic ceramics, as shown in figure 2-4. The most developed composites to

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[68] Larry R. Johnson, Arvind T.S. Teotia, and Lawrence G. Hill, "A Structural Ceramic Research Program: A Preliminary Economic Analysis," Argonne National Laboratory, ANL/CNSV-38, 1983.

[69] Charles River Associates, op. cit., footnote 48.

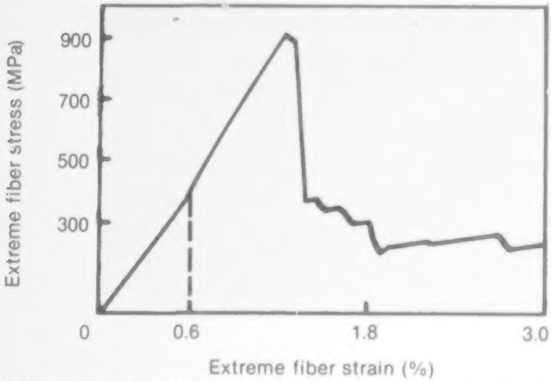
[70] Richerson, op. cit., footnote 4.

[71] Ibid.

[72] Ibid.

[73] Ibid.

Figure 2-4.—Load-Deflection Curve for a Nicalon Fiber-Reinforced Silicon Nitride Composite



Dotted line indicates point at which fracture would occur without fiber reinforcement.

SOURCE: Joseph N. Panzarino, Norton Co., personal communication, Sept. 3, 1987.

date are silicon carbide fiber-reinforced glass-ceramic matrices.

Recent analysis suggests that fibers resist the opening of a matrix crack by frictional forces at the matrix-fiber interface.[74] One of the important results is that the strength of the composite becomes *independent* of preexisting flaw size. This means that strength becomes a well-defined property of the material, rather than a statistical distribution of values based on the flaw populations.

CMCs present an opportunity to design composites for specific engineering applications. This will require a detailed understanding of the micromechanics of failure and explicit quantitative relations between mechanical properties and microstructural characteristics. The most important breakthrough in ceramic composites will come with the development of new high-temperature fibers that can be processed with a wider range of matrix materials.

New Processes for Ceramics

Several forming and sintering techniques may offer the potential for significant improvements in the microstructures of ceramics produced from powders. These include advanced casting methods, such as open casting and centrifugal casting; and such new heating methods as microwave and plasma sintering.[75]

In the future, however, chemical approaches to the fabrication of ceramics will probably be preferred to the traditional methods of grinding and pressing powders. Chemical routes to ceramics include such techniques as sol-gel processing, chemical vapor infiltration of ceramic fiber preforms, and in-situ formation of metal-ceramic composites by reactions between liquid metals and appropriate gases.[76] [77] These techniques afford greater control over the purity of the ceramic and over its microstructure. It has been estimated that 50 percent of structural ceramics will be processed chemically by the year 2010.[78]

Biotechnology

Structural ceramics could have a significant interaction with the developing field of biotechnology in the future. Ceramics could be used extensively in fermenters, and they are likely to be important in a broad range of product separation technologies.

Fermenters

Most current fermenters are made of 316 grade stainless steel.[79] Steel fermenters suffer from several disadvantages, including contamination of the cultures with metal ions, corrosion caused by cell metabolites or reagents, and leaks around gaskets and seals during sterilization and temperature cycling.

Glass-lined steel bowls are sometimes used, especially for cell cultures, which are more sensitive to contamination than bacterial cultures. However, the thermal expansion mismatch between the glass lining and the metal causes problems during steam sterilization.

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[74] D.B. Marshall and A.G. Evans, "The Mechanics of Matrix Cracking in Brittle-Matrix Fiber Composites," *Acta Metallurgica* 33(11):2013-2014, 1985.

[75] Richard Pober, Ceramics Processing Research Laboratory, MIT, personal communication, April 1987.

[76] See for example David W. Johnson, Jr., "Sol-Gel Processing of Ceramics and Glass," *American Ceramic Society Bulletin* 64(12): 1597-1602, 1985.

[77] Commonly called the Lanxide process, this technique has recently been extended to permit the fabrication of ceramic fiber-reinforced composites. See *Materials and Processing Report*, MIT Press, vol. 2, June 1987.

[78] R. Nathan Katz, presentation at the Society of Automotive Engineers International Congress and Exposition, Detroit, MI, February 1986.

[79] Richard F. Geoghegan, E.I. du Pont de Nemours & Co., personal communication, August 1986.

Ceramics offer a solution to these problems because of their chemical stability and low thermal expansion. Ceramics could be used in the bowl and agitator, as well as in the peripheral plumbing joints and agitator shaft seal to prevent leaking.

Separation Technology

Separation and purification of the products of cell and bacterial cultures is a key aspect of biotechnology. In general, the separation techniques are based less on filtration than on active interactions between a solid phase and the liquid mixture, as in chromatography. For instance, biologically produced insulin is now being purified with a chromatographic process based on a modified silica material.[80] Silica or alumina particles can also be used as a solid support for attaching monoclonal antibodies, which bind to specific proteins and effect a separation by affinity chromatography.[81]

The strength and hardness of the ceramics are key to the avoidance of deformation of the ceramic particles under conditions of high throughput.[82] In the future, the most efficient processes could be hybrids based on both filtration and chromatography.[83] As these processes are scaled up to production units, there will probably be a large increase in the demand for specially modified silica and alumina column packing materials.

Energy Production

Power Turbines

The performance requirements for power turbines are much greater than those for automotive gas turbines.[84] Power turbines must have a lifetime of 100,000 hours, compared with about 3,000 hours for the auto turbine. In addition, the consequences of power turbine failure are much greater. In light of these facts, a recent report has concluded that power turbines will be commercialized after automotive gas turbines.[85]

Although some of the processing technology developed for the auto turbine may be applicable to power turbines, the scale-up from a rotor having a 6-inch diameter to one having a much larger diameter may require completely new fabrication techniques. The larger ceramic structures may also require different NDE techniques to ensure reliability.

Thus, use of monolithic ceramics in the critical hot-section components of power turbines is not anticipated in the next 25 years. However, ceramics may find applications in less critical structures, such as combustor linings. In addition, ceramic coatings could be used to augment the high-temperature resistance of cooled superalloy rotor blades.[86]

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[80] Joseph J. Kirkland, E.I. du Pont de Nemours & Co., personal communication, August 1986.

[81] George Whitesides, Department of Chemistry, Harvard University, personal communication, August 1986.

[82] Ibid.

[83] Michelle Betrido, Celanese Research Corp., personal communication, August 1986.

[84] Johnson and Rowcliffe op. cit., footnote 43.

[85] Ibid.

[86] Ibid.

RESEARCH AND DEVELOPMENT PRIORITIES

In fiscal year 1987, the U.S. Government spent about $65 million on structural ceramics R&D (table 2-10). R&D expenditures in private industry may be roughly comparable.[87] [88] DOE and DoD spent the largest proportions, at 55 and 28 percent, respectively. The following hierarchy of R&D priorities are based on the opportunities identified above. These are then correlated with the actual spending on structural ceramics R&D in fiscal year 1985.

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[87] Charles River Associates, op. cit., footnote 48, p. 38.

[88] A recently completed survey by the United States Advanced Ceramics Association places the private industry R&D investments in all advanced ceramics, including structural and electronic ceramics, at $153 million in 1986, somewhat greater than the total government expenditure of $100 to $125 million.

Table 2-10.—Structural Ceramic Technology: Federal Government Funded R&D (in millions of dollars)

	FY 1983	FY 1984	FY 1985	FY 1986	FY 1987
Department of Energy:					
Conservation and renewable energy:					
Vehicle propulsion	11.4	12.7	11.9	10.0	12.0
Advanced materials	3.2	5.1	6.0	8.7	14.0
Industrial programs	1.0	2.3	1.7	1.5	1.9
Energy utilization research	0.5	1.5	1.8	1.8	2.0
Fossil energy:					
Advanced research and technology development	1.0	1.1	1.5	1.2	1.9
Energy research:					
Basic energy science	3.0	4.4	4.6	4.5	4.2
NASA:					
Lewis Research Center	3.0	2.5	5.4	4.5[a]	4.6[a]
National Science Foundation	2.9	3.3	3.6	3.6	3.7
National Bureau of Standards				2.2	3.0
Department of Defense:					
Defense ARPA	7.7	8.2	9.4	10.0	7.3
U.S. Air Force	3.0	3.4	4.7	4.7	5.1
U.S. Army	4.7	6.0	2.5	4.4[b]	3.6[c]
U.S. Navy	1.2	1.3	1.4	2.3	1.9
Total	42.6	51.8	54.5	59.4	65.2

[a] Includes $1.6 million for Manpower Salaries.
[b] Includes $4.0 million for TACOM Diesel.
[c] Includes $2.0 million for TACOM Diesel.

SOURCE: Robert B. Schulz, Department of Energy.

Very Important

Processing Science

There is a great need for generic research to support the development of practical manufacturing technologies within industry. The agenda for such research is long, but includes such topics as:

- development of near-net-shape processes;
- development of pure, reproducible powders, whiskers, and fibers that can be formed and densified with a minimum of intermediate steps; role of solution chemistry in powder preparation and control of interface properties in CMCs;
- development of practical in-process inspection devices and techniques to identify problems at the earliest possible stage in the process;
- iterative development of new equipment such as hot isostatic presses (HIPs) and multistage processes such as sinter-HIP, with emphasis on scaling up to commercially viable size; and
- understanding of the relationships between coating process variables and final properties and performance of ceramic coatings.

Environmental Behavior

Many of the applications for ceramics mentioned above require long-term performance in severe environments. To develop higher temperature, corrosion-resistant materials, it is necessary to understand the long-term behavior of candidate ceramic materials in the anticipated environments:

- For heat engine applications, the general requirement is to understand the mechanical and chemical behavior of advanced ceramics such as silicon nitride, silicon carbide, zirconia, and CMCs based on these materials in environments of 1000° to 1400° C (1832° to 2552° F) in air, carbon monoxide, and carbon dioxide.
- In ceramic wear parts, it is necessary to understand the interrelationships of wear, erosion, and toughness in the presence of lubricating fluids and gases. Generally, wear parts include hard materials such as tungsten carbide, titanium diboride, and materials that have good lubrication characteristics, such as silicon nitride.
- Because heat exchangers generally fail as a result of slow corrosion at high temperatures, it is important to understand the chemical

processes of corrosion in such environments as salts of sodium, potassium, magnesium, calcium, vanadium, and mixed metals. In addition to existing materials (e.g., silicon carbide, cordierite, and zirconium silicate), newer materials, including silicon nitride and CMCs, should be investigated. Corrosion-resistant ceramic coatings may become important here.

- Considering the large size of the potential markets in bioceramics, it is critical to understand the long-term effects of body fluids on chemical structure and mechanical properties. In view of the many years that ceramic implants must serve without failure, the interaction between slow crack growth and the body environment should be investigated.
- The long-term environmental stability of advanced chemically bonded ceramics is crucial to their effectiveness in construction and other applications. The deterioration of the properties of some advanced cements in the presence of moisture remains a problem, and the chemical degradation of the fiber interface in reinforced cements and concretes has limited the structural uses of these materials.

Reliability

No factor is more important to the success of ceramics in all of the applications discussed than reliability. Because the performance specifications and environment of each application are different, it is necessary to establish the most appropriate and cost-effective NDE methods for each one.

To distinguish between critical flaws and harmless flaws, models need to be developed for predicting the service life of ceramic parts containing various kinds of flaws. Such models must depend heavily on information derived from the categories of environmental behavior of ceramics and CMC failure mechanisms discussed above. Beyond a dependence on intrinsic flaws in the material, however, service life also depends on the location and nature of the flaw within the structure itself. It is not sufficient to characterize the behavior of a coupon of the material from which a structure is made; either the structure itself must be tested or additional models must be available to predict the effects of a particular flaw on a particular structure.

Interphase in CMCs

The interphase between ceramic fiber and matrix is critical to the static strength, toughness, and long-term stability of the CMC. Very little is known about the relationship between the properties of the interphase and these overall CMC properties. The capability to modify the surface chemistry of ceramic fibers and whiskers to provide optimum compatibility between reinforcement and matrix could yield remarkable improvements in ceramic performance and reliability.

Important

Joining of Ceramics

In most applications, ceramics are not used alone; rather, ceramic components are part of larger assemblies. Therefore, the ceramic must be joined to more conventional materials in the assembly to function properly. Broad research on joining of ceramics to metals, glasses, and other ceramics could have a decisive impact on future use of monolithic ceramics, coatings, and CMCs.

The key to joining is an understanding of the surface properties of the two materials and of the interface between them. In general, the interface is a critical point of weakness in discrete ceramic components such as those in heat engines, in ceramic coatings on metal substrates, and in ceramic fibers in CMCs.

Principal needs in this area are in the strengthening and toughening of joints, an understanding of their high-temperature chemistry, and improved resistance to corrosion in the various environments of interest. As with solution methods in powder preparation, chemistry will make a crucial contribution in this area.

Tribology of Ceramics

Tribology, the study of friction, wear, and lubrication of contiguous surfaces in relative motion, is of key importance in terms of ceramic wear parts and heat engine components. Lubrication is a particularly serious problem in ceramic engines because of their high operating temperatures.

Ordinary engine oils cannot be used above about 350° F (177° C). For operating temperatures of 500° to 700° F (260° to 371° C), synthetic liquids such as polyol esters are available, but are extremely expensive and require further development. In a low-heat rejection (adiabatic) ceramic engine, cylinder liner temperatures may reach 1000° to 1700° F (538° to 927° C), depending on the insulating effectiveness of major engine components. For this elevated temperature regime, synthetic lubricants cannot be used effectively.

One approach to this problem is to use solid lubricants that would become liquid at elevated temperatures; however, no such lubricants exist for use in the environments envisioned (high-temperature, corrosive gases). Moreover, the distribution of solid lubricant around the engine is a persistent problem.[89]

A second method involves modifications of the surface of the component to produce self-lubrication. The lubricant can be introduced through ion implantation directly into the surface (to a depth of several micrometers) of the component; it then diffuses to the surface to reduce friction. Some metal or boron oxides show promise as lubricants. Alternatively it is possible to use surface coatings of extremely hard ceramics such as the carbides and nitrides of zirconium, titanium, or hafnium, without any lubrication. At present, these techniques all lead to sliding friction coefficients that are roughly four times higher than those achieved at low temperatures with engine oils.[90] Further research is clearly needed.

Failure Mechanisms in CMCs

CMCs offer the best solution to the problem of the brittleness of ceramics. However, this field is still in its infancy, and research is characterized by a very empirical approach to mixing, forming, densification, and characterization of fiber-powder combinations. Fundamental understanding of the failure mechanisms in CMCs would provide guidance for development of new, tougher ceramics. This would include investigation of: multiple toughening techniques, such as transformation toughening and whisker reinforcement; the role of interphase properties in fracture; and failure mechanisms in continuous-fiber CMCs.

Desirable

Chemically Bonded Ceramics

Chemically bonded ceramics (CBCs) offer great promise for low-cost, net-shape fabrication of structures in such applications as wear parts and construction. Recent improvements in the tensile strength of CBCs suggest that the limits of this key engineering property are far from being realized. Further research is required in reduction of flaw size, long-term stability in various environments, and the properties of the interphase in fiber-reinforced cements and concretes.

* * *

Table 2-11 shows that the actual structural ceramics R&D spending in fiscal year 1985 for all government agencies corresponds roughly with the priority categories recommended above, although specific projects differ. Processing research accounted for the lion's share, with 76 percent. No separate estimate was available of research on the interphase in CMCs; a portion of this work is included under CMC fabrication, listed here as a subcategory of processing. Also, no separate figure was obtained for Federal expenditures on advanced cements and concretes. In fiscal year 1983, however, total U.S. Government and industry funding of cement research was estimated at only $1 million, compared with a portland cement sales volume over $1 billion.[91] Assuming that the current breakdown of Federal ceramics research is similar to that in fiscal year 1985, a comparison of table 2-11 with the priorities listed above suggests that greater emphasis should be placed on joining, tribology, and cement-based materials.

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[89] Manfred Kaminsky, Surface Treatment Science International, personal communication, August 1986.

[90] Ibid.

[91] National Research Council, Transportation Research Board, op. cit., footnote 30.

Table 2-11.—Breakout of the Fiscal Year 1985 Structural Ceramics Budget According to the R&D Priorities Cited in the Text

Research area	FY 1985 budget percentage
Processing:	
Powder synthesis	4
Monolithic fabrication	32
Composite fabrication	32
Component design and testing	4
Coatings	4
Machining	<1
Subtotal	76
Environmental behavior	4
Reliability:	
Modeling	2
Time dependent behavior	1
Nondestructive evaluation	3
Microstructure evaluation	4
Subtotal	10
Interphase in composites	no separate figure
Tribology	2
Joining	3
Fracture	5
Standards	<1
Total	100%

SOURCE: S.J. Dapkunas, National Bureau of Standards, unpublished survey, 1985.

Chapter 3

Polymer Matrix Composites

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Chapter 3

Polymer Matrix Composites

FINDINGS

Polymer matrix composites (PMCs) are comprised of a variety of short or continuous fibers bound together by an organic polymer matrix. Unlike a ceramic matrix composite (CMC), in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a PMC provides high strength and stiffness. The PMC is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement. The function of the matrix is to bond the fibers together and to transfer loads between them.

Polymer matrix composites are often divided into two categories: reinforced plastics, and "advanced composites." The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-stiffness glass fibers. Advanced composites, which have been in use for only about 15 years, primarily in the aerospace industry, have superior strength and stiffness, and are relatively expensive. Advanced composites are the focus of this assessment.

Chief among the advantages of PMCs is their light weight coupled with high stiffness and strength along the direction of the reinforcement. This combination is the basis of their usefulness in aircraft, automobiles, and other moving structures. Other desirable properties include superior corrosion and fatigue resistance compared to metals. Because the matrix decomposes at high temperatures, however, current PMCs are limited to service temperatures below about 600° F (316° C).

Experience over the past 15 years with advanced composite structures in military aircraft indicates that reliable PMC structures can be fabricated. However, their high cost remains a major barrier to more widespread use in commercial applications. Most advanced PMCs today are fabricated by a laborious process called lay-up. This typically involves placement of sequential layers of polymer-impregnated fiber tapes on a mold surface, followed by heating under pressure to cure the lay-up into an integrated structure. Although automation is beginning to speed up this process, production rates are still too slow to be suitable for high-volume, low-cost industrial applications such as automotive production lines. New fabrication methods that are much faster and cheaper will be required before PMCs can successfully compete with metals in these applications.

Applications and Market Opportunities

Aerospace applications of advanced composites account for about 50 percent of current sales. Sporting goods, such as golf clubs and tennis rackets, account for another 25 percent. The sporting goods market is considered mature, with projected annual growth rates of 3 percent. Automobiles and industrial equipment round out the current list of major users of PMCs, with a 25 percent share.

The next major challenge for PMCs will be use in large military and commercial transport aircraft. PMCs currently comprise about 3 percent of the structural weight of commercial aircraft such as the Boeing 757, but could eventually account for more than 65 percent. Because fuel savings are a major reason for the use of PMCs in commercial aircraft, fuel prices must rise to make them competitive.

The largest volume opportunity for PMCs is in the automobile. PMCs currently are in limited production in body panels, drive shafts, and leaf springs. By the late 1990s, PMC unibody structures could be introduced in limited production. Additional near-term markets for PMCs include medical implants, reciprocating industrial machinery, storage and transportation of corrosive chemicals, and military vehicles and weapons.

Beyond the turn of the century, PMCs could be used extensively in construction applications such as bridges, buildings, and manufactured housing. Because of their resistance to corrosion, they may also be attractive for marine structures. Realization of these opportunities will depend on development of cheaper materials and on designs that take advantage of compounding benefits of PMCs, such as reduced weight and increased durability. In space, a variety of composites could be used in the proposed aerospace plane, and PMCs are being considered for the tubular frame of the NASA space station.

Research and Development Priorities

Unlike most structural ceramics, PMCs have compiled an excellent service record, particularly in military aircraft. However, in many cases the technology has outrun the basic understanding of these materials. To generate improved materials and to design and manufacture PMCs more cost-effectively, the following needs should be addressed:

- **Processing Science:** Development of new, low-cost fabrication methods will be critical for PMCs. An essential prerequisite to this is a sound scientific basis for understanding how process variables affect final properties.
- **Impact Resistance:** This property is crucial to the reliability and durability of PMC structures.
- **Delamination:** A growing body of evidence suggests that this is the single most important mode of damage propagation in PMCs with laminar structures.
- **Interphase:** The poorly understood interfacial region between the fiber and matrix has a critical influence on PMC behavior.

INTRODUCTION

Unlike a ceramic matrix composite, in which the reinforcement is used primarily to improve the fracture toughness, the reinforcement in a polymer matrix composite provides strength and stiffness that are lacking in the matrix. The composite is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement. The function of the relatively weak matrix is to bond the fibers together and to transfer loads between them. As with CMCs, the reinforcement may consist of particles, whiskers, fibers, or fabrics, as shown in figure 3-1.

PMCs are often divided into two categories: reinforced plastics, and so-called advanced composites. The distinction is based on the level of mechanical properties (usually strength and stiffness); however, there is no unambiguous line separating the two. Reinforced plastics, which are relatively inexpensive, typically consist of polyester resins reinforced with low-stiffness glass fibers (E-glass). They have been in use for 30 to 40 years in applications such as boat hulls, corrugated sheet, pipe, automotive panels, and sporting goods.

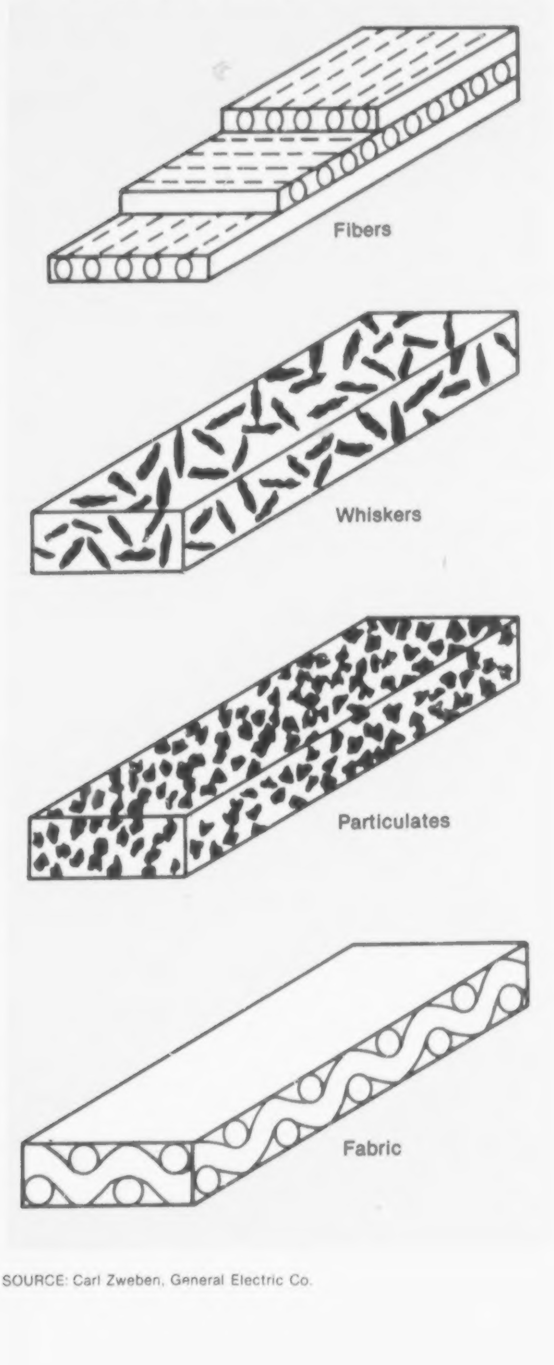
Advanced composites, which have been in use for only about 15 years, primarily in the aerospace industry, consist of fiber and matrix combinations that yield superior strength and stiffness. They are relatively expensive and typically contain a large percentage of high-performance continuous fibers, such as high-stiffness glass (S-glass), graphite, aramid, or other organic fibers. This assessment primarily focuses on market opportunities for advanced composites.

Less than 2 percent of the material used in the reinforced plastics/PMCs industry goes into advanced composites for use in high-technology applications such as aircraft and aerospace.[1] In

---

[1] These advanced composites are primarily epoxy matrices reinforced with carbon fibers. Reginald B. Stoops, R.B. Stoops & Associates, Newport, RI, "Manufacturing Requirements of Polymer Matrix Composites," contractor report for OTA, December 1985.

Figure 3-1.—Composite Reinforcement Types



SOURCE: Carl Zweben, General Electric Co.

1985, the worldwide sales of advanced composite materials reached over $2 billion. The total value of fabricated parts in the United States was about $1.3 billion split among three major industry categories: 1) aerospace (50 percent), 2) sports equipment (25 percent), and 3) industrial and automotive (25 percent).[2]

It has been estimated that advanced composites consumption could grow at the relatively high rate of about 15 percent per year in the next few years, with the fastest growing sector being the aerospace industry, at 22 percent. By 1995, consumption is forecast to be 110 million pounds with a value (in 1985 dollars) of about $6.5 billion. By the year 2000, consumption is forecast to be 200 million pounds, valued at about $12 billion.[3]

Based on these forecasts, it is evident that the current and near-term cost per pound of advanced composite structure is roughly $60 per pound. This compares with a value of about $1 per pound for steel or $1.50 per pound for glass fiber-reinforced plastic (FRP). If these forecasts are correct, it is clear that over this period (to the year 2000), advanced composites will be used primarily in high value-added applications that can support this level of material costs. However, use of PMCs can lead to cost savings in manufacturing and service. Thus, the per-pound cost is rarely a useful standard for comparing PMCs with traditional materials.

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[2] Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, March 1987.

[3] "Industry News," *SAMPE Journal*, July/August 1985, p. 89.

CONSTITUENTS OF POLYMER MATRIX COMPOSITES

Matrix

The matrix properties determine the resistance of the PMC to most of the degradative processes that eventually cause failure of the structure. These processes include impact damage, delamination, water absorption, chemical attack, and high-temperature creep. Thus, the matrix is typically the weak link in the PMC structure.

The matrix phase of commercial PMCs can be classified as either thermoset or thermoplastic. The general characteristics of each matrix type are shown in figure 3-2; however, recently developed matrix resins have begun to change this picture, as noted below.

Thermosets

Thermosetting resins include polyesters, vinylesters, epoxies, bismaleimides, and polyimides. Thermosetting polyesters are commonly used in fiber-reinforced plastics, and epoxies make up most of the current market for advanced composites resins. Initially, the viscosity of these resins is low; however, thermoset resins undergo chemical reactions that crosslink the polymer chains and thus connect the entire matrix together in a three-dimensional network. This process is called curing. Thermosets, because of their three-dimensional crosslinked structure, tend to have high dimensional stability, high-temperature resistance, and good resistance to solvents. Recently, considerable progress has been made in improving the toughness and maximum operating temperatures of thermosets.[4]

Thermoplastics

Thermoplastic resins, sometimes called engineering plastics, include some polyesters, polyetherimide, polyamide imide, polyphenylene sulfide, polyether-etherketone (PEEK), and liquid crystal polymers. They consist of long, discrete molecules that melt to a viscous liquid at the processing temperature, typically 500° to 700° F (260° to 371° C), and, after forming, are cooled to an amorphous, semicrystalline, or crystalline solid. The degree of crystallinity has a strong effect on the final matrix properties. Unlike the curing process of thermosetting resins, the processing of thermoplastics is reversible, and, by simply reheating to the process temperature, the resin can be formed into another shape if desired. Thermoplastics, although generally inferior to thermosets in high-temperature strength and chemical stability, are more resistant to cracking and impact damage. However, it should be noted that recently developed high-performance thermoplastics, such as PEEK, which have a semicrystalline microstructure, exhibit excellent high-temperature strength and solvent resistance.

Thermoplastics offer great promise for the future from a manufacturing point of view, because it is easier and faster to heat and cool a material than it is to cure it. This makes thermoplastic matrices attractive to high-volume industries such as the automotive industry. Currently, thermoplastics are used primarily with discontinuous-fiber reinforcements such as chopped glass or carbon/graphite. However, there is great potential for high-performance thermoplastics reinforced with continuous fibers. For example, thermoplas-

Figure 3-2.—Comparison of General Characteristics of Thermoset and Thermoplastic Matrices

Resin type	Process temperature	Process time	Use temperature	Solvent resistance	Toughness
Thermoset	Low	High	High	High	Low
Toughened thermoset	↑	↓	↑	↑	↓
Lightly crosslinked thermoplastic					
Thermoplastic	High	Low	Low	Low	High

SOURCE: Darrel R. Tenney, NASA Langley Research Center.

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[4] See, for instance, *Aerospace America*, May 1986, p. 22.

tics could be used in place of epoxies in the composite structure of the next generation of fighter aircraft.

Reinforcement

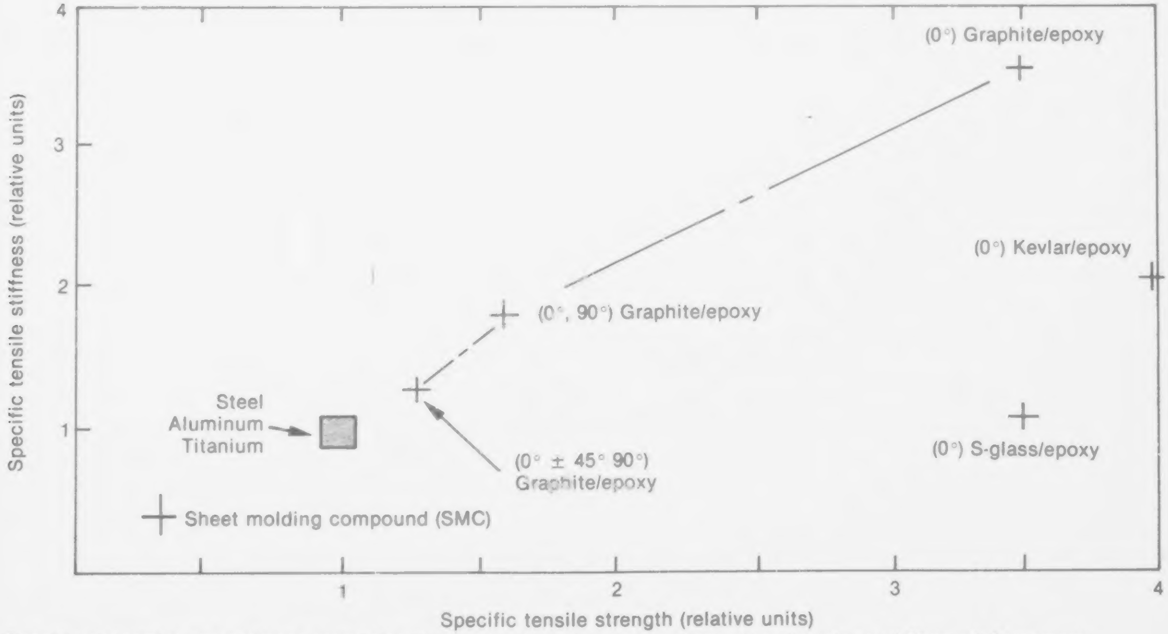
The continuous reinforcing fibers of advanced composites are responsible for their high strength and stiffness. The most important fibers in current use are glass, graphite, and aramid. Other organic fibers, such as oriented polyethylene, are also becoming important. PMCs contain about 60 percent reinforcing fiber by volume. The strength and stiffness of some continuous fiber-reinforced PMCs are compared with those of sheet molding compound and various metals in figure 3-3. For instance, unidirectional, high-strength graphite/epoxy has over three times the specific strength and stiffness (specific properties are ordinary properties divided by density) of common metal alloys.

Of the continuous fibers, glass has a relatively low stiffness; however, its tensile strength is competitive with the other fibers and its cost is dramatically lower. This combination of properties is likely to ensure that glass fibers remain the most widely used reinforcement for high-volume commercial PMC applications. Only when stiffness or weight are at a premium would aramid and graphite fibers be used.

Interphase

The interphase of PMCs is the region in which loads are transmitted between the reinforcement and the matrix. The extent of interaction between the reinforcement and the matrix is a design variable, and it may vary from strong chemical bonding to weak frictional forces. This can often be controlled by using an appropriate coating on the reinforcing fibers.

Figure 3-3.—Comparison of the Specific Strength and Stiffness of Various Composites and Metals[a]



Specific properties are ordinary properties divided by density; angles refer to the directions of fiber reinforcement

[a] Steel: AISI 4340; Aluminum: 7075-T6; Titanium: Ti-6Al-4V.

SOURCE: Carl Zweben, General Electric Co.

Generally, a strong interfacial bond makes the PMC more rigid, but brittle. A weak bond decreases stiffness, but enhances toughness. If the interfacial bond is not at least as strong as the matrix, debonding can occur at the interphase under certain loading conditions. To maximize the fracture toughness of the PMC, the most desirable coupling is often intermediate between the strong and weak limits. The character of the interfacial bond is also critical to the long-term stability of the PMC, playing a key role in fatigue properties, environmental behavior, and resistance to hot/wet conditions.

PROPERTIES OF POLYMER MATRIX COMPOSITES

The properties of the PMC depend on the matrix, the reinforcement, and the interphase. Consequently, there are many variables to consider when designing a PMC. These include not only the types of matrix and reinforcement but also their relative proportions, the geometry of the reinforcement, and the nature of the interphase. Each of these variables must be carefully controlled to produce a structural material optimized for the conditions for which it is to be used.

The use of continuous-fiber reinforcement confers a directional character, called anisotropy, to the properties of PMCs. PMCs are strongest when stressed parallel to the direction of the fibers (0°, axial, or longitudinal, direction) and weakest when stressed perpendicular to the fibers (90°, transverse direction). In practice, most structures are subjected to complex loads, necessitating the use of fibers oriented in several directions (e.g., 0, ±45, 90°). However, PMCs are most efficiently used in applications that can take advantage of the inherent anisotropy of the materials, as shown in figure 3-3.

When discontinuous fibers or particles are used for reinforcement, the properties tend to be more isotropic because these reinforcements tend to be randomly oriented. Such PMCs lack the outstanding strength of continuous-fiber PMCs, but they can be produced more cheaply, using the technologies developed for unreinforced plastics, such as extrusion, injection molding, and compression molding. Sheet molding compound (SMC) is such a material, widely used in the automotive industry; see figure 3-3.

The complexity of advanced composites can complicate a comparison of properties with conventional materials. Properties such as specific strength are relatively easy to compare. Advanced composites have higher specific strengths and stiffnesses than metals, as shown in figure 3-3. In many cases, however, properties that are easily defined in metals are less easily defined in advanced composites. Toughness is such a property. In metals, wherein the dynamics of crack propagation and failure are relatively well understood, toughness can be defined relatively easily. In an advanced composite, however, toughness is a complicated function of the matrix, fiber, and interphase, as well as the reinforcement geometry.[5] Shear and compression properties of advanced composites are also poorly defined.

Another result of the complexity of PMCs is that the mechanical properties are highly interdependent. For instance, cracking associated with shear stresses may result in a loss of stiffness. Impact damage can seriously reduce the compressive strength of PMCs. Compressive and shear properties can be seen to relate strongly to the toughness of the matrix, and to the strength of the interfacial bond between matrix and fiber.

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[5] Given that perfect composite toughness cannot be attained, in some cases a material with lower toughness may be preferable to one with higher toughness. A brittle composite with low impact resistance may shatter upon impact, while a slightly tougher composite may suffer cracking. For some applications, even slight cracking may be unacceptable, and impossible to repair. If the composite shatters in the region of impact, but no cracking occurs in the surrounding material, the damage may be easier to repair.

DESIGN, PROCESSING, AND TESTING

Design

Advanced composites are designed materials. This is really the fact that underlies their usefulness. Given the spectrum of matrix and reinforcement materials available, properties can be optimized for a specific application. An advanced composite can be designed to have zero coefficient of thermal expansion. It can be reinforced with combinations of fiber materials (hybrid PMCs) and geometries to maximize performance and minimize cost. The design opportunities of PMC materials are only beginning to be realized.

The enormous design flexibility of advanced composites is obtained at the cost of a large number of unfamiliar design variables. In fact, composites are more accurately characterized as customized structures, rather than materials. Although the engineering properties of the homogeneous resins and fibers can be determined, the properties of each composite depend on the composition, fiber geometry, and the nature of the interphase. However, the categories of mechanical and physical properties used to characterize PMCs are carried over from long engineering experience with metals.

A major need in advanced composites technology is a better capability for modeling structure-property relationships (discussed in more depth in ch. 5). In spite of this lack, however, experience to date has shown that designers and manufacturers can produce reliable PMC structures. This is probably due to two factors. First, in the face of uncertainty, designers tend to overdesign; that is, they are conservative in their use of material, to avoid any possibility of material failure. Second, PMC structures are extensively tested before use, ensuring that any potential problems show up during the tests. Thus, the PMC materials themselves have been proven, in the sense that structures can be fabricated that are reliable and meet all design criteria. However, both overdesign and empirical testing are costly and drive up the prices of PMCs. Thus, a principal benefit of enhanced modeling capability will be to help make advanced composites more cost-competitive.

Manufacturing

Given the many different fibers and matrices from which PMCs can be made, the subject of PMC manufacturing is an extremely broad one. However, more than any other single area, low-cost manufacturing technologies are required before advanced composites can be used more widely. The basic steps include: 1) impregnation of the fiber with the resin, 2) forming of the structure, 3) curing (thermoset matrices) or thermal processing (thermoplastic matrices), and 4) finishing.

Depending on the process, these steps may occur separately or continuously. For instance, the starting material for many PMCs is a prepreg; i.e., a fiber tape or cloth that has been preimpregnated with resin and partially cured. In pultrusion, by contrast, impregnation, forming, and curing are done in one continuous process. Some of the more important fabrication processes for PMCs are listed in table 3-1.

In the aerospace sector, advanced composite structures are commonly fabricated by the slow and labor-intensive process of hand lay-up of

Table 3-1.—Production Techniques for Polymer Composites

Technique	Characteristics	Examples
Sheet molding	Fast, flexible, 1-2" fiber	SMC automotive body panels
Injection molding	Fast, high volume very short fibers, thermoplastics	Gears, fan blades
Resin transfer molding	Fast, complex parts, good control of fiber orientation	Automotive structural panels
Prepreg tape lay-up	Slow, laborious, reliable, expensive (speed improved by automation)	Aerospace structures
Pultrusion	Continuous, constant cross-section parts	I-beams, columns
Filament winding	Moderate speed, complex geometries, hollow parts	Aircraft fuselage, pipes, drive shafts
Thermal forming (future)	Reinforced thermoplastic matrices; fast, easy repair, joining	All of above

SOURCE: Office of Technology Assessment, 1988.

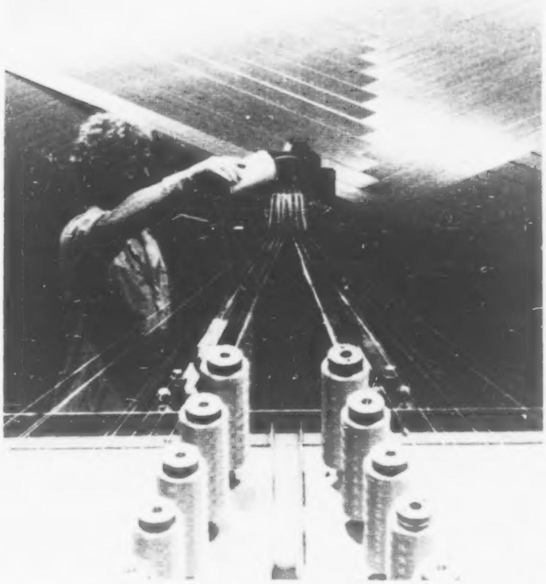

Photo credit: Hercules, Inc.

Filament winding of a rocket motor case.

prepreg tapes. Hand lay-up involves placement of sheets or tapes of prepreg on a tool (the contoured surface that defines the shape of the finished part). Labor costs often dominate the production costs of these PMC structures. In the case of a business aircraft fuselage, material costs have been estimated at about $13,000 per unit; labor costs, about $21,000 per unit; and capital costs, about $1,400 per unit.[6] These labor cost estimates include 1,154 person-hours for hand lay-up of the stiffeners and honeycomb core of the fuselage; only 35 person-hours are required to produce the inner and outer advanced composite skins, which can be fabricated by the automated filament winding process.[7]

New, more automated processes are now available that offer dramatic increases in productivity over hand lay-up. One project underway in-house at an airframe manufacturer can lay up to 100 feet of 3- or 6-inch wide prepreg tape per minute, in complex shapes of variable thickness.[8] At least one machine tool manufacturer is developing a system of automated tape laying that takes into account the specified contour of the mold, and aligns the tape according to tape width and desired gap between strips, laying the tape along a precomputed path.

Most of these processes have been explored for thermosetting advanced composites for aircraft applications such as ailerons, stabilizers, flaps, fins, and wing skins; in addition there has also been some work done in the area of auto-

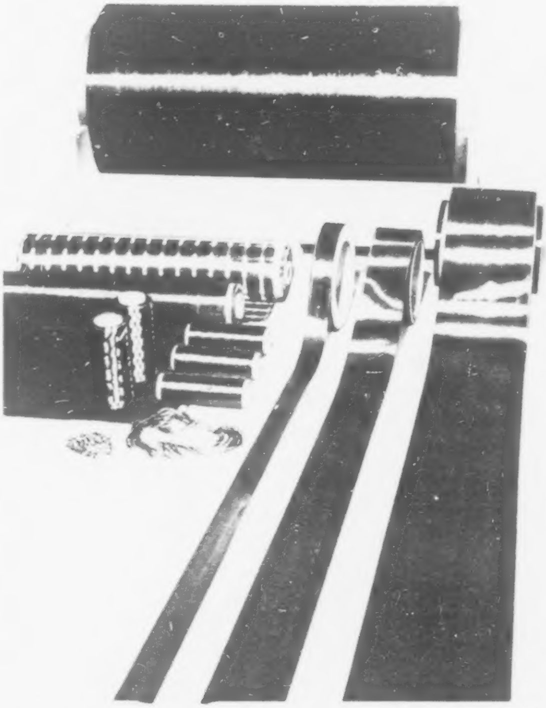

Photo credit: Hercules Inc.

Graphite fiber reinforcement forms. Top: broadgoods; right: prepreg tape; left (front): chopped fiber and carbon fiber rope; left (rear): fabric and fabric prepreg.

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[6] Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites," in conjunction with Massachusetts Institute of Technology, a contractor report prepared for OTA, December 1985.

[7] Ibid.

[8] "Rockwell Team Demonstrates Automatic Construction of Large Composite Wings," *Aviation Week & Space Technology*, June 15, 1987, p. 336.

mated tape laying for continuous fiber-reinforced thermoplastic sheets, laid in parallel strips and continuously fused as they are placed.[9]

Nondestructive Evaluation

In general, PMCs do not have as great a tendency to brittle fracture as do ceramics. This means that the critical flaw size in large PMC structures may be of the order of centimeters, whereas in ceramics, it is some tens of microns. Advanced composite structures are increasingly used in life-critical structures such as aircraft wings and fuselages. This places a special burden on nondestructive evaluation (NDE), both in the factory and in the field.

Although NDE is now used primarily for the detection of defects in finished structures, in the future it could be used increasingly for monitoring the status of PMCs at intermediate steps in the production process. Progress in this field will require development of sophisticated sensors and feedback control systems.

Requirements for NDE of PMCs differ somewhat from those for ceramics. Although the flaw sizes to be detected are not as small, the area of structure to be investigated is frequently much larger, up to hundreds of square feet. Thus, NDE techniques are required that can rapidly scan large areas for flaws or damage. Even though there are numerous techniques that may be useful in the laboratory for testing small specimens for research purposes, relatively few are appropriate to production or field-level inspection.

Several of the more important NDE techniques that are relevant to production, end product, and field level inspection are listed in table 3-2. Excellent progress has been made in production level techniques such as ultrasonics, and manufacturers are confident that large PMC surface areas can be inspected reliably and economically for such flaws as bulk delaminations.

The inspection and repair of PMC structures (e.g., aircraft components) at the depot and field levels will require a substantial training program for inspectors unfamiliar with PMCs. All procedures must be standardized and straightforward because, in general, PMC experts will not be available. In the future, as inspection processes become fully computerized, this could be an excellent application for automated systems that can guide the operator through the process and alert him to any detected anomalies.

Table 3-2.—NDE Techniques Appropriate for Production, Finished Product, Depot-, and Field-Level Inspections of Polymer Matrix Composite Structures

NDE technique	Flaw type	Sensitivity	Complex shapes	Development for commercialization
Production:				
Visual (remote)	Fiber orientation, foreign material	good	good	none
Ultrasonic	Porosity, viscosity during cure	good	poor	extensive
Dielectrometry	Degree of cure	good	good	some
End product:				
Visual	Surface	good	good	none
Ultrasonic	Bulk	good	poor	some
Radiographic	Bulk	fair	excellent	none
Acoustic emission	Bulk	fair	good	extensive
Depot level:				
Ultrasonic	Bulk delamination	good	poor	some
Field level:				
Ultrasonic	Bulk delamination	fair	poor	extensive

SOURCE: Joseph A. Moyzis, et al., "Nondestructive Testing of Polymer Matrix Composites," a contractor report prepared for OTA, December 1985.

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[9] Roger Seifried, Cincinnati Miliacron, personal communication, June 1, 1987.

HEALTH AND SAFETY

There are a number of unique health and safety issues associated with the manufacture of PMC materials. The health hazards associated with the manufacture of PMC materials stem from the fact that chemically active materials are used and workers handling them may breathe harmful fumes or come into contact with irritating chemicals. The chemical of greatest concern is the styrene monomer used in polyester resins. The problem is most severe when the resin is sprayed, and the monomer evaporates into the air. Inhalation of styrene monomer can cause headaches, dizziness, or sore throat. In fact, some people become sensitized to the vapors and they can no longer work in a reinforced plastics plant.

The Occupational Health and Safety Administration (OSHA) has specified that styrene monomer concentrations in a plant should not exceed 100 parts per million.[10] In a plant in which spray systems are used, extensive air-handling equipment, spray booths, and air masks are required to maintain these standards. Where polyester resins are used for compression molding, resin transfer molding, or other enclosed mold systems, the problem can be dealt with by use of simple exhaust systems.

A new safety hazard was introduced with the advent of carbon fibers. They tend to float around the plant in which they are used. Because they are electrical conductors, they can get into unprotected electrical devices and cause short circuits. The fiber concentration in the air can be controlled by a negative pressure exhaust system in the area in which they are used, but all electrical devices in the area should be sealed to make them explosion proof. Because most factories using carbon fibers are generally involved with advanced composites and are more sophisticated than most reinforced plastics plants, they are able to handle this hazard without undue difficulty.

Recycling and Disposal

Most PMC materials in use today have thermosetting matrices; consequently, after they have been cured, they have no apparent scrap value. Although attempts have been made to grind them up and use them as fillers, this has not proven to be economically practical. The reuse of uncured PMCs offers little economic incentive; most scrap is simply discarded. By contrast, one of the potential advantages of PMCs with thermoplastic matrices is that the scrap can be recycled.

Cured PMCs present no particular disposal problem; they are chemically inert and can be used for landfill. Incineration is generally avoided because it can generate toxic smoke.

The principal problem associated with PMC disposal arises with uncured PMCs. Wet lay-ups, prepregs, SMC, etc. are still chemically active and pose both health and safety problems. If used in landfill, the active chemicals can leach out and cause contamination of the soil or water. A more serious problem is that the catalyzed resins may go on to cure and generate an exotherm that causes spontaneous combustion or self-ignition. The safe way to dispose of uncured PMC material is to bake it until it is cured and then dispose of it.

APPLICATIONS AND MARKETS

PMCs are a more mature technology than structural ceramics. With the experience gained in military applications such as fighter aircraft and rocket motor casings beginning in the 1970s, advanced composites now have a good record of performance and reliability. They are rapidly becoming the baseline structural material of the defense/aerospace industry.

Because of their high cost, diffusion of advanced composites into the civilian economy is likely to be a top-down process, progressing from relatively high value-added applications such as aircraft to automobiles and then to the relatively low-technology applications such as construction, which generally requires standardized shapes such as tubes, bars, beams, etc. On the other hand, there is also a bottom-up process at work in which savings in manufacturing costs permit unreinforced engineering plastics and short fiber-reinforced PMCs to replace metals in applications in which high strength and stiffness are not required, such as use of SMC for automobile body panels.

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[10] *World of Composites*, quarterly publication of the SPI Reinforced Plastics/Composites Institute, winter 1986.

Applications and markets for PMCs are discussed according to end-user industry below.

Aerospace

The aerospace industry is estimated to consume about 50 percent of advanced composites production in the United States.[11] Growth projections for aerospace usage of advanced composites have ranged from 8.5 percent per year[12] to 22 percent per year.[13] Advanced composites are used extensively today in small military aircraft, military and commercial rotorcraft, and prototype business aircraft. The next major aircraft market opportunity for advanced composites is in large military and commercial transport aircraft.

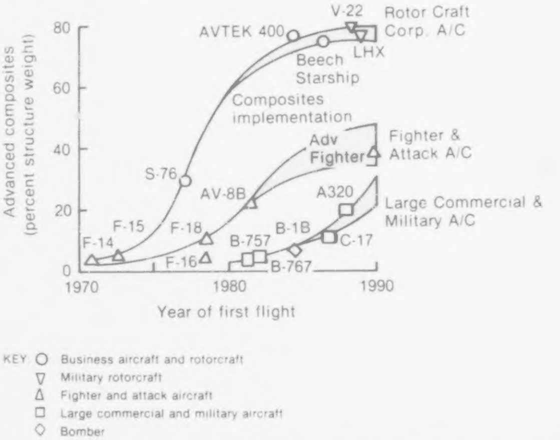
The primary matrix materials used in aerospace applications are epoxies, and the most common reinforcements are carbon/graphite, aramid (e.g., Du Pont's Kevlar), and high-stiffness glass fibers. However, high-temperature thermoplastics such as PEEK are considered by many to be the matrices of choice for future aerospace applications.

Compared with metals, the principal advantages of advanced composites in aerospace applications are their superior specific strength and stiffness, resulting in weight savings of 10 to 60 percent over metal designs, with 20 to 30 percent being typical.[14] This weight reduction can be used to increase range, payload, maneuverability and speed, or to reduce fuel consumption. It has been estimated that a pound of weight saved on a commercial transport aircraft is worth $100 to $300 over its service life, depending on the price of fuel, among other factors.[15] This high premium for weight saved is unique to this aerospace sector, and explains why it leads all others in advanced composite market growth rate. Additional advantages of advanced composites are their superior fatigue and corrosion resistance, and vibration-damping properties.

Military Aircraft

Advanced composites have become essential to the superior performance of a large number of fighter and attack aircraft (figure 3-4). Because the performance advantages of advanced composites in military aircraft more than compensate for their high cost, this is likely to be the fastest growing market for advanced composites over the next decade. Indications are that composites may account for up to 40 percent of the struc-

Figure 3-4.—Composite Aircraft Structure (by percent)



SOURCE: Richard N. Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structure of High Performance Aircraft," a presentation to the National Research Council, Aeronautics and Space Engineering Board, Naval Postgraduate School, Monterey, CA, Feb. 10, 1986.

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[11] Strategic Analysis, Inc., op. cit., March 1987.

[12] According to "Worldwide High Performance Composites," a market study conducted by Frost & Sullivan, New York, NY, as reported in *World of Composites*, a publication of the Society of Plastics Industries, winter 1986, p. 4.

[13] According to a market study by Charles H. Kline & Co., "Advanced Polymer Composites," Fairfield, NJ, reported in *Plastics Engineering*, June 1985, p. 62.

[14] Carl Zweben, "Polymer Matrix Composites," *Frontiers in Materials Technologies*, M.A. Meyers and O.T. Inal (eds.) (The Netherlands: Elsevier Science Publishers, 1985), ch. 12, p. 365.

[15] Bob Hammer, Boeing Commercial Aircraft Co., personal communication, August 1986.

Photo credit: Hercules, Inc.

A modern lightweight fighter incorporating 64 different components—more than 900 pounds of composite structure per airplane.

tural weight of the Advanced Tactical Fighter (ATF), which is still in the design phase. One estimate, which assumes only existing production plus the ATF, projects a growth from about 0.3 million pounds per year in 1985 to 2 million pounds per year in 1995.[16]

Commercial Aircraft

If aramid and glass fiber-reinforced composites are included, the volume of composites used in commercial and business aircraft is about twice that used in military aircraft.[17] In current commercial transport aircraft, such as the Boeing 767, advanced composites make up about 3 percent of the structural weight, and are used exclusively in the secondary (not flight-critical) structure.[18] However, two companies, Beechcraft and Avtek, are anticipating Federal Aviation Administration (FAA) certification of "all-composite aircraft prototypes for business use in 1988 and 1990, respectively.[19]

Although overall growth of the business aircraft fleet through the early 1990s is expected to be only around 10 percent, two categories (turboprops and turbojets) are expected to grow significantly.[20] These aircraft are also the best candidates for composite fuselages. The estimated value (derived from cost and volume estimates) of composite fuselages, assuming all business aircraft manufacturers adopt this technology, is about \$100 million per year.[21] These fuselages could account for 1.2 million pounds of graphite/epoxy consumption annually. Large transport or commercial aircraft fuselages will probably not be made from advanced composites until the technology is demonstrated in business aircraft.

By the year 2000, PMCs could make up 65 percent of the structural weight of commercial transport aircraft.[22] Estimating a structural weight of 75,000 pounds per aircraft and production of 500 aircraft per year, this application alone should account for 24 million pounds of advanced composites per year. Assuming a starting material value of \$60 per pound, the market in the year 2000 is projected to be worth about \$1.5 billion for the composite materials alone. A much more conservative estimate, which assumes that no new commercial aircraft will be built by 1995, has placed the U.S. composite commercial airframe production at only 1 million to 2 million pounds in that year.[23]

Helicopters

With the exception of the all-composite business aircraft prototypes, which are still awaiting certification, advanced composites have been used more extensively in helicopters than in aircraft. Military applications have led the way, and the advantages of advanced composites are much the same as in aircraft: weight reduction, parts consolidation, and resistance to fatigue and corrosion.

Over the past 15 years, advanced composites have become the baseline materials for rotors, blades, and tail assemblies. Sikorsky's S-76 commercial model, which is about 25 percent advanced composite by weight (figure 3-4), was certified in the late 1970s. Future military helicopters, such as the Army's proposed LHX (with major airframe design teams at Bell/McDonnell Douglas and Boeing/Sikorsky), or the Navy's tilt-rotor V-22 Osprey (designed by Bell/Boeing) have specifications that require designers to consider advanced composites. In these helicopters, composites are likely to comprise up to 80 percent of the structural weight (figure 3-4).

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[16] Richard N. Hadcock, Grumman Aircraft Systems Division, "Status and Viability of Composite Materials in Structures of High Performance Aircraft," a presentation to the National Research Council, Aeronautics and Space Engineering Board, Naval Postgraduate School, Monterey, CA, Feb. 10, 1986.

[17] Ibid.

[18] Darrel R. Tenney, NASA Langley Research Center, "Advanced Composite Materials: Applications and Technology Needs," presentation to the Metal Properties Council, Inc., Miami, FL, Dec. 5, 1985.

[19] According to information supplied by Beechcraft and Avtek.

[20] Materials Modeling Associates, op. cit., footnote 6, 1985.

[21] Ibid.

[22] Tenney, op. cit., footnote 18.

[23] Hadcock, op. cit., footnote 16.

Materials such as graphite/epoxy are likely to be used in the airframe, bulkheads, tail booms, and vertical fins, while glass/epoxy PMCs of lesser stiffness could be used in the rotor systems. As with aircraft, there could be a long-term trend away from epoxy resins and toward thermoplastic resins.

Automotive Industry

The automotive industry is widely viewed as being the industry in which the greatest volume of advanced composite materials could be used in the future. (See ch. 7 for a case study examining the use of PMCs for automobile body structures.) Because the industry is mature and highly competitive, the principal motivation for introducing PMCs is cost savings.

In contrast to the aircraft industry, there is no clear-cut premium associated with a pound of weight saved. Nevertheless, the automotive industry continues to be interested in saving weight as it pursues the conflicting goals of larger automobiles and higher fuel efficiency. Automakers are looking to the vehicle skin/frame systems to provide the next big leap in weight reduction. Other potential technical advantages of PMCs, such as corrosion resistance, appear to be secondary to the cost issue.

By far the greatest volume of PMC material in use is sheet molding compound (SMC), used in nonstructural parts such as exterior panels. The most visible automotive use of SMC in recent years has been in the Pontiac Fiero, which has an all-PMC exterior.[24]

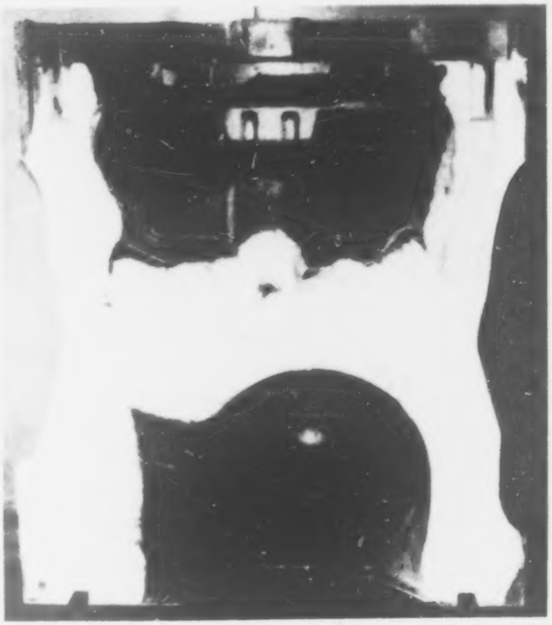

Photo credit: Ford Motor Co.

Compression molded composite rear floor pan prototype for the Ford Escort. Ten steel components were consolidated into a single molding, with 15 percent weight savings.

The next major opportunity for PMCs in automobiles is in structural components.[25] Two structural components currently in service are the advanced composite drive shaft and leaf spring. Some 3,000 drive shafts, manufactured by filament winding of graphite and E-glass fibers in a polyester resin, were used annually in the Ford Econoline van.[26] Meanwhile, glass FRP springs in the Corvette and several other models are in production at the rate of approximately 600,000 per year. Leaf springs are regarded as a very promising application of PMCs, and they are expected to show strong growth, especially in light trucks. Prototype primary body structures have been constructed with weight savings of 20 percent or more.

Engineering groups within the Big Three U.S. automobile producers are considering advanced composite unibody vehicle designs for the late 1990s.[27] The automakers are exploring PMC frames for a variety of reasons. PMC vehicles would enable designers to reduce the number of parts required in assembly; some manufacturers are looking into a one-piece advanced composite body. By reducing the number of parts, better consistency of parts can be achieved at considerably reduced assembly costs.

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[24] The Fiero will be cancelled at the end of 1988.

[25] P. Beardmore, "Composite Structures for Automobiles," *Composite Structures*, vol. 5, 1986, pp. 163-176.

[26] Although composite drive shafts are technically successful, Ford took them out of production in 1987 in favor of a new aluminum design.

Advanced composites also offer substantial improvements in specific mechanical properties, with the possibility of reducing weight while increasing strength and stiffness. Finally, because they do not rust, PMCs offer greatly improved corrosion resistance over steel or galvanized steel. Analysts have estimated that PMC automobiles could last 20 or more years, compared to the current average vehicle lifetime of 10 years.[28]

The major technical barrier to use of PMCs in the automotive industry is the lack of manufacturing technologies capable matching the high production rates of metal-stamping technology (see ch. 7). The fastest current technologies can process material at the rate of tens of pounds per minute, but true economy will require rates of a hundred pounds per minute or more.[29] Thus, there is a gap of roughly an order of magnitude between current and economical rates.

Reciprocating Equipment

PMC materials have considerable potential for use in many different kinds of high-speed industrial machinery. Current applications include such components as centrifuge rotors, weaving machinery, hand-held tools, and robot arms. All of these applications take advantage of the low inertial mass, but they also benefit to varying degrees from the tailorable anisotropic stiffness, superior strength, low thermal expansion, and fatigue-life and vibration-damping characteristics of PMCs.

In robotic applications, increasing both the speed and the endpoint accuracy of the robot are desired improvements. Stiffness is the key mechanical property in that the endpoint accuracy is limited by bending deflections in the beam-shaped robot members. With metal designs, stiffness is obtained at the cost of higher mass, which limits the robot's response time. Consequently, the ratio of the weight of the manipulator arm to that of the payload is rarely lower than 10:1.[30] Because of their superior stiffness per unit weight, PMCs are a promising solution to this problem. At present, only one U.S. company has marketed a robot incorporating PMCs,[31] although there are several Japanese models on the market and a number of other countries are funding research.

Although the benefits of using PMCs in reciprocating equipment are clear, initial attempts to penetrate this market have been disappointing. The market is a highly fragmented one, and equipment manufacturers, who tend to be oriented toward metals, have shown a reluctance to consider the use of a higher cost material (particularly when its use requires new processes and tooling) even when performance advantages are demonstrated. No attempt has been made to quantitatively estimate future markets. PMC penetration is likely to be slow but steady.

Naval Applications

The light weight and corrosion resistance of PMCs makes them attractive for a number of naval applications. Advanced composites are currently in production in molded propeller assemblies for the Mark 46 torpedo, at a cost savings of 65 to 70 percent over the previous aluminum design.[32] The Navy is also evaluating PMCs for hatch doors, bulkheads, and propeller shafts. PMC components in the ship superstructure have the dual advantage of lowering the center of mass (and therefore increasing the stability) and pro-

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[27] Materials Modeling Associates, op. cit., footnote 6, 1985.

[28] Ibid.

[29] Charles Segal, Omnia, in OTA workshop on "Future Applications of Advanced Composites," Dec. 10, 1985.

[30] B.S. Thompson and C.K. Sung, "The Design of Robots and Intelligent Manipulators Using Modern Composite Materials," *Mechanism and Machine Theory* 20:471-82, 1985.

[31] Graco Robotics of Lavonia, MI, manufactures a spray painting robot with a hollow graphite/epoxy arm. However, this is being phased out in favor of a new aluminum design.

[32] Ronald L. Pegg and Herbert Reyes, "Progress in Naval Composites," *Advanced Materials and Processes*, March 1987, p. 35.

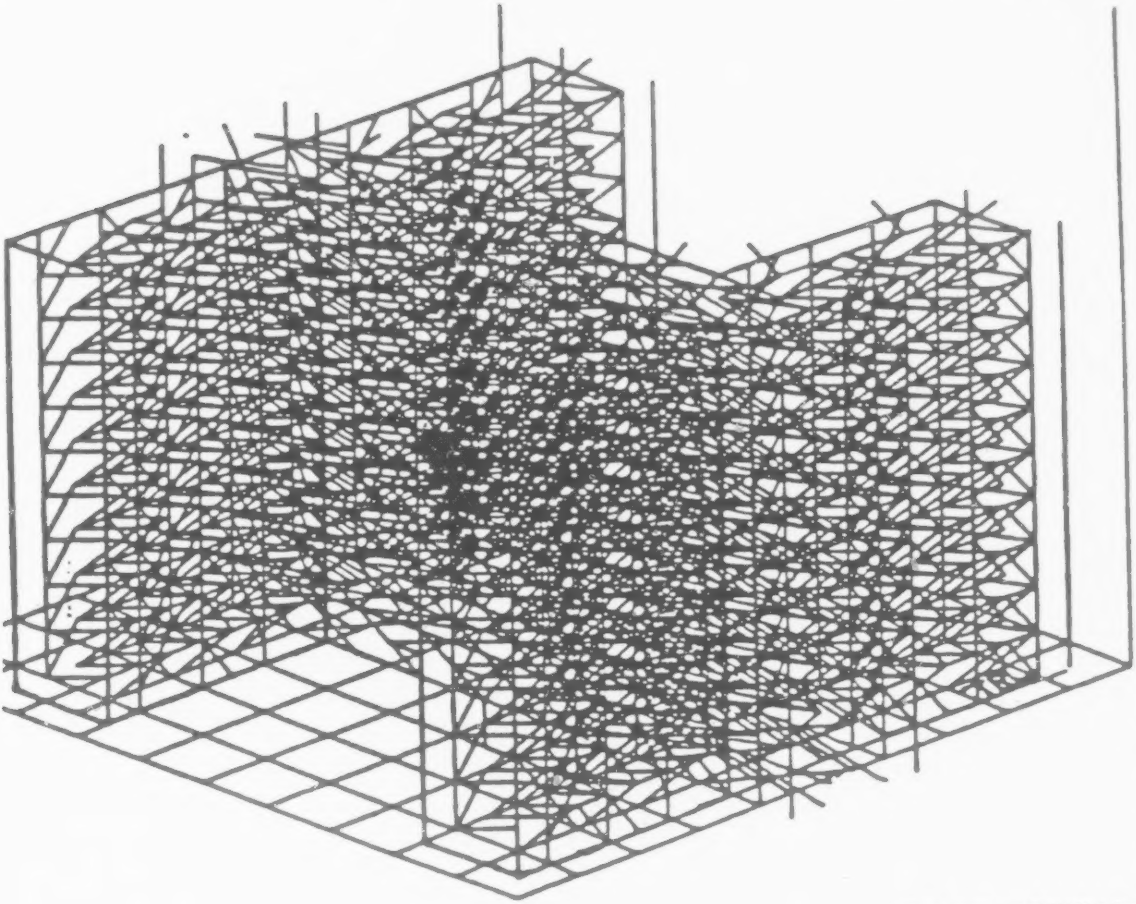

Photo credit: The CUMAGNA Corp.

Computer trace of fiber paths in a three-dimensional braided I-beam. This process yields a composite I-beam which is strong in all directions, but which weighs much less than steel.

viding better protection against shrapnel fragments in combat. PMCs have also been in use for years as sonar domes on submarines, and radomes for surface ships.

Future applications for PMCs on surface ships include antenna masts and stacks (due to reduced weight and radar cross section), and valves, pipes, and ducts (due to lower weight and corrosion resistance). PMCs could also be used for an advanced technology submarine hull, providing weight savings and thus speed advantages over metal hulls currently in use.

Construction

A potentially high-volume market for PMCs lies in construction applications, especially in construction of buildings, bridges, and housing. Additional applications include lampposts, smokestacks, and highway culverts. Construction equipment, including cranes, booms, and outdoor drive systems, could also benefit from use of PMCs. Because of the many inexpensive alternative building materials currently being used, the cost of PMC materials will be the key to their use in this sector.

The chief advantage of using PMCs in construction would be reduced overall systems costs for erecting the structure, including consolidation of fabrication operations, reduced transportation and construction costs due to lighter weight structures, and reduced maintenance and lifetime costs due to improved corrosion resistance.[33]

Bridges are likely to be the first large-scale construction application for PMCs in the United States. Because the largest load that must be supported by the bridge is its own dead weight, use of lightweight advanced composites would allow the bridge to accommodate increased traffic or heavier trucks. Decking materials are likely to be relatively inexpensive vinylester or epoxy resins reinforced with continuous glass fibers. Cables would probably be reinforced with graphite or aramid fibers, because of the high stiffness and low creep requirements.

The opportunities for use of PMCs in bridges are considerable: most highway bridges in the United States are over 35 years old, and most railroad bridges are over 70 years old.[34] Replacing or refurbishing even a small fraction of these with PMC materials would involve a substantial volume of fiber and resin. However, significant technical, economic, and institutional barriers exist to the implementation of this technology, such that construction opportunities should be viewed as long term. Nevertheless, the U.S. Department of Transportation is currently evaluating PMCs for use in bridge decking and stay cables.[35] Fiberglass tendons are also being used in place of steel in prestressed concrete bridge structures.[36] Other countries that have active programs in this area include China, Great Britain, West Germany, Israel, and Switzerland.

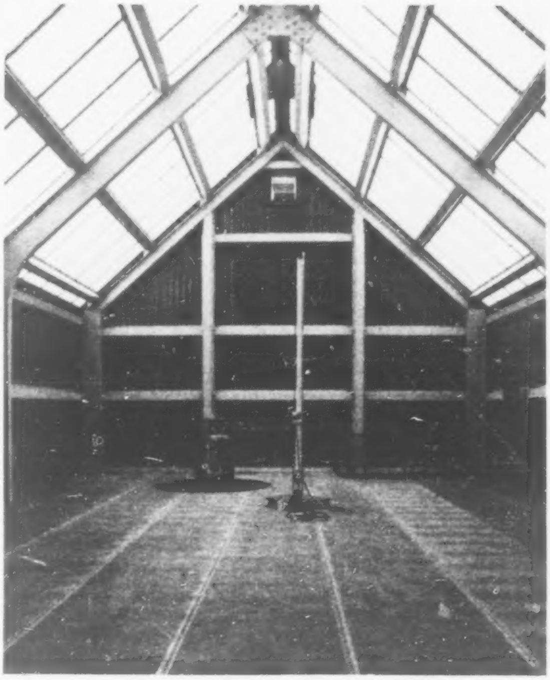

Photo credit: Composite Technology, Inc.

Interior of a nonmetallic, nonmagnetic structure built for Apple Computer, Inc., to house a microwave device testing facility. The building components, including fasteners, are entirely made of fiber-reinforced composites.

The manufactured housing industry is an especially intriguing potential opportunity for PMC materials. In 1984, almost half of all new housing units were partially manufactured; that is, large components were built in factories, rather than assembled on site.[37] In the future, factory manufacture of housing promises to reduce housing costs while still maintaining options for distinctive designs. PMC manufacturing techniques such as pultrusion and transfer molding could be used to fabricate integral wall structures containing structural members and panels constructed in a single step. Components such as I-beams, angles, and channels can also be economically produced by these techniques. In spite of the opportunities, however, Japan and several countries in Europe are far ahead of the United States in housing construction technologies.

One important research need affecting the use of PMCs in construction applications has to do with adhesion and joining. The joining of PMC materials to other materials for the purpose of load transfer, or to themselves for the purpose of manufacturing components, requires advances in technology beyond present levels. This is a particular obstacle when joining may be done by unskilled labor. A second need for PMCs use in the construction industry involves the availability of standardized shapes of standard PMC materials to be purchased much the way metal shapes are currently sold for construction use.

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[33] Howard Smallowitz, "Reshaping the Future of Plastic Buildings," *Civil Engineering*, May 1985, pp. 38-41.

[34] John Scalzi, National Science Foundation, personal communication, August 1986.

[35] According to information provided by Craig A. Ballinger, Federal Highway Administration, August 1986.

[36] *Engineering News Record*, Aug. 29, 1985, p. 11.

[37] Thomas E. Nutt-Powell, "The House That Machines Built," *Technology Review*, November 1985, p. 31.

An additional technical barrier is need for development of design techniques for integrated, multifunctional structures. Window frames made by joining together several pieces of wood can be replaced by molded plastic and PMC structures having many fewer pieces, lower assembly costs, and better service performance. The flexibility of the design and manufacture of PMC materials could also be used to integrate a window frame into a larger wall section, again reducing the number of parts and the cost of manufacture. This has already been done for certain experimental bathroom structures in which lavatories, shower rooms, and other structural components have been integrated in a single molding.[38]

The principal barriers to the adoption of new materials technologies in the construction industry in the United States are not so much technological as institutional and economic. Like the highway construction industry, the housing construction industry is highly fragmented. This makes the rate of research and development investment and adoption of new technology very low. The performance of housing materials is regulated by thousands of different State and local building and fire safety codes, all written with conventional materials in mind. Further, engineers and contractors lack familiarity with the PMC materials and processes. Finally, PMCs must compete with a variety of low-cost housing materials in current use. As a result, PMCs used in manufactured housing are not likely to be advanced; rather, they are likely to consist of wood fibers pressed with inexpensive resins or laminated structures involving FRP skin panels glued to a foam or honeycomb core.

Medical Devices

PMC materials are currently being developed for medical prostheses and implants. The impact of PMCs on orthopedic devices is expected to be especially significant. Although medical devices are not likely to provide a large volume market for PMCs, their social and economic value are likely to be high.

The total estimated world market for orthopedic devices such as hips, knees, bone plates, and intramedullary nails is currently about 6 million units with a total value of just over $500 million.[39] Estimates of the U.S. market for all biocompatible materials by the year 2000 range up to $3 billion per year.[40] PMCs could capture a substantial portion of that, sharing the market with ceramics and metals.

Metallic implant devices, such as the total hip unit that has been used since the early 1960s, suffer a variety of disadvantages: difficulty in fixation, allergic reactions to various metal ions, poor matching of elastic stiffness, and mechanical (fatigue) failure.

PMC materials have the potential to overcome many of these difficulties. Not only can the problem of metal ion release be eliminated, but PMC materials can be fabricated with stiffness that is tailored to the stiffness of the bone to which they are attached, so that the bone continues to bear load, and does not resorb (degenerate) due to absence of mechanical loading. This is a persistent problem with metal implants.

It is also possible to create implants from biodegradable PMC systems that would provide initial stability to a fracture but would gradually resorb over time as the natural tissue repairs itself. In addition, PMCs can be designed to serve as a scaffold for the invasive growth of bone tissue as an alternative to cement fixation. This leads to a stronger and more durable joint.

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[38] Kenneth L. Reifsnider, Materials Response Group, Virginia Polytechnic Institute, "Engineering Research Needs of Polymer Composites," a contractor report prepared for OTA, December 1985.

[39] Ibid.

[40] Larry L. Hench and June Wilson, "Biocompatibility of Silicates for Medical Use," *Silicon Biochemistry*, CIBA Foundation Symposium No. 121 (Chichester, England: John Wiley & Sons, 1986), pp. 231-246.

Research in PMC orthopedic devices is currently being carried out on a relatively small scale in the laboratories of orthopedic device manufacturers. Further research is required to improve in situ strength and service life, stress analysis, and fabrication and quality control technologies.

To overcome the remaining technical barriers, a cooperative effort of interdisciplinary teams is required. At a minimum, a team must include expertise in design, engineering, manufacturing, and orthopedic surgery. Significant strides in this field are being made in Japan, Great Britain, France, West Germany, Italy, Canada, and Australia, as well as in the United States.[41]

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[41] Reifsnider, op. cit., footnote 38.

FUTURE TRENDS IN POLYMER MATRIX COMPOSITES

Novel Reinforcement Types

Rigid Rod Molecules

PMCs can be reinforced with individual, rigid rod-like molecules or with fibers generated from these molecules. One example is poly (phenylbenzobisthiazole), or PBT. Experimental fibers made from this material have specific strength and stiffness on a par with the most advanced fiber reinforcement, exceeding the properties of commercially available metals, including titanium, by more than a factor of 10.[42] One particularly promising possibility is to dissolve the molecular rods in a flexible polymer and thus create a PMC reinforced by individual molecules. Such a homogeneous composition would mitigate the problem of matching the thermal expansion coefficient between the reinforcement and the matrix, and it would virtually eliminate the troublesome interface between them. The future of this technology will depend on solving the problems of effectively dissolving the rods in the matrix and of orienting them once dissolved.

Novel Matrices

Because the matrix largely determines the environmental durability and toughness, the greatest improvements in the performance of future PMCs will come from new matrices, rather than new fibers. Perhaps the most significant opportunities lie in the area of molecular design; chemists will be able to design polymer molecules to have the desired flexibility, strength, high-temperature resistance, and adhesive properties.[43] Some of the more promising directions are discussed below.

Oriented Molecular Structures

At present the anisotropic properties of most PMCs are determined by the directions of fiber orientation. In the future, it may be possible to orient the individual polymer molecules during or after polymerization to produce a self-reinforced structure. The oriented polymers could serve the same reinforcing function as fibers do in today's PMCs. In effect, today's organic fibers (e.g., Du Pont's Kevlar or Allied's Spectra 900), which consist of oriented polymers and which have among the highest specific stiffness and strength of all fibers, provide a glimpse of the properties of tomorrow's matrices.

Recently developed examples of oriented polymer structures are the liquid crystal polymers (LCPs). They consist of rigid aromatic chains modified by thermoplastic polyesters (e.g., polyethyleneterephthalate, or PET), or polyaramids. They have a self-reinforcing fibrous character that imparts strength and stiffness comparable to those of reinforced thermoplastic molding compounds, such as 30 percent glass-reinforced nylons.[44] The fiber orientations of current LCPs are hard to control (current applications include microwave cookware and ovenware that require high-temperature resistance but not high strength) and this represents a challenge for the future.

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[42] Thaddeus Helminiak, "Hi-Tech Polymers From Ordered Molecules," *Chemical Week*, Apr. 11, 1984.

[43] Charles P. West, Resin Research Laboratories, Inc., personal communication, August 1986.

[44] Reginald B. Stoops, "Ultimate Properties of Polymer Matrix Materials," contractor report prepared for OTA, December 1985.

High-Temperature Matrices

The maximum continuous service temperature of organic polymers in an oxidizing atmosphere is probably around 700° F,[45] although brief exposures to higher temperatures can be tolerated. Currently, the most refractory matrices are polyimides, which can be used at a maximum temperature of 600° F (316° C), although slow degradation occurs.[46] If stable, high-temperature matrices could be developed, they would find application in a variety of engine components and advanced aircraft structures.

Thermotropic Thermosets

These hybrid matrices are designed to exploit the processing advantages of thermoplastics and the dimensional stability and corrosion resistance of thermosets. The molecules are long, discrete chains that have the latent capacity to form crosslinks. Processing is identical to thermoplastics in that the discrete polymers are formed at high temperatures to the desired shape. Then, however, instead of cooling to produce a solid, the structure is given an extra kick, with additional heat or ultraviolet light, which initiates crosslinking between the polymer chains. Thus, the finished structure has the dimensional stability characteristic of a thermoset.[47]

Space Applications

Space Transportation Systems

Over 10,000 pounds of advanced composites are used on the space shuttle.[48] Advanced composites are also being considered in designs for a proposed National Aerospace Plane (NASP), although such an aircraft probably will not be available until after the year 2000. The primary limitation on the use of advanced composites in this application would be high temperature.[49] Flying at speeds exceeding Mach 7, the lower surfaces and leading edges would experience temperatures of 2,000 to 3,000° F (1,093 to 1,649° C).[50] If advanced composites were available that could retain high strength and stiffness up to 800° F (427° C), they could be used extensively for the cooler skin structure and most of the substructure.

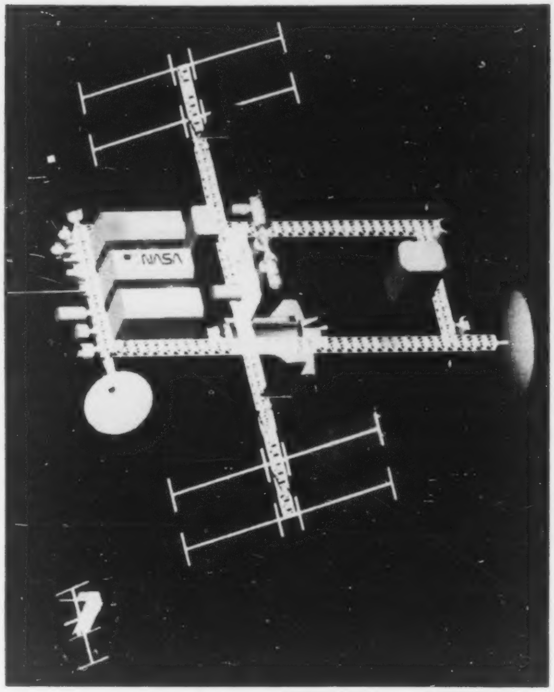

Photo credit: National Aeronautics and Space Administration

Reference configuration for the NASA manned space station. Composites could be used in the tubular struts which make up the frame.

Space Station

Graphite/epoxy advanced composites and aluminum are both being considered for the tubular struts in the space station reference design. The goal of reducing launch weight favors the use of advanced composites; however, their lower thermal conductivity (compared with aluminum) could create problems in service. The most serious environmental problem faced by advanced composites is temperature swings between −250°

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[45] Paul McMahan, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials," Dec. 10, 1985.

[46] *Aerospace America*, May 1986, p. 22.

[47] John Riggs, Celanese Research Corp., in an OTA workshop, "Future Opportunities for the Use of Composite Materials," Dec. 10, 1985.

[48] Tenney, op. cit., footnote 18.

[49] Hadcock, op. cit., footnote 16.

[50] Ibid.

F (−121° C) and +200° F (+93° C) caused by periodic exposure to the Sun. This thermal cycling produces radial cracks in graphite/epoxy tubes that can reduce the torsional stiffness by as much as 30 percent after only 500 cycles.[51] To reduce the effects of thermal cycling, advanced composite tubes would be coated with a reflecting, thermally conducting layer to equalize the temperature throughout the tube. The layer would also protect the PMC from atomic oxygen (a major cause of material degradation in low-Earth orbit), and solar ultraviolet radiation.

Military

Composites of all types, including ceramic, polymer, and metal matrix composites, are ideal materials for use in space-based military systems, such as those envisioned for the Strategic Defense Initiative.[52] Properties such as low density, high specific stiffness, low coefficient of thermal expansion, and high temperature resistance are all necessary for structures that must maneuver rapidly in space, maintain high dimensional stability, and withstand hostile attack. A program devoted to the development of new materials and structures has been established within the Strategic Defense Initiative Office.[53]

Bioproduction

Living cells can synthesize polymeric molecules with long chains and complex chemistries that cannot be economically reproduced in the laboratory. For instance, crops and forests are an important source of structural materials and chemical feedstocks. Several plants such as crambe and rapeseed, and certain hardwood trees, are now being evaluated for commercial production of lubricants, engineering nylons, and PMCs.[54] For some materials, such as natural rubber, the United States is totally dependent on foreign sources. In the Critical Agricultural Materials Act of 1984 (Public Law 98-284), Congress mandated that the Department of Agriculture establish an Office of Critical Materials to evaluate the potential of industrial crops to replace key imported materials. Several demonstration projects of 2,000 acres or more were started in 1987.

With the possible exception of wood, it is unlikely that biologically produced materials will compete seriously with PMCs in the structural applications discussed in this report. Although natural polymers such as cellulose, collagen, and silk can have remarkably high strength, their low stiffness is likely to limit their use in many structures. Nevertheless, their unique chemical and physical properties make them appropriate for certain specialty applications. For instance, collagen is a biologically compatible material that is used to generate artificial skin.[55]

Biotechnology may offer a novel approach to the synthesis of biological polymers in the future. Genetically engineered bacteria and cells have been used to produce proteins related to silk.[56] In the future, production rates could be accelerated by extracting the protein synthetic machinery from the cells and driving the process with an external energy source, such as a laser or electric current.[57] The flexibility inherent in such a scheme would be enormous; by simply altering the genetic instructions, new polymers could be produced.

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[51] Tenney, op. cit., footnote 18.

[52] Jerome Persh, "Materials and Structures, Science and Technology Requirements for the DOD Strategic Defense Initiative," *American Ceramic Society Bulletin* 64(4):555-559, 1985.

[53] The effort includes: lightweight structures; thermal and electrical materials; optical materials and processes; tribological materials; and materials durability. In 1988, budgets for these materials programs were about $26 million, and are projected to reach $54 million in 1989.

[54] According to information supplied by the USDA's Office of Critical Materials.

[55] J. Burke, et al., "The Successful Use of Physiologically Acceptable Artificial Skin in the Treatment of Extensive Burn Injury," *Annals of Surgery*, vol. 194, 1982, pp. 413-28.

[56] Dennis Lang, Syntro Corp., personal communication, August 1986.

[57] Terrence Barrett, National Aeronautics and Space Administration, personal communication, August 1986.

RESEARCH AND DEVELOPMENT PRIORITIES

Federal R&D spending for PMCs in fiscal years 1985 to 1987 is shown in table 3-3; roughly 70 to 80 percent in each year was spent by the Department of Defense. The large drop in Federal expenditures from 1985 to 1986 does not reflect a sharp cut in PMC R&D; rather, it can be attributed to the completion of large research programs in 1985 and the transitioning of the technology (particularly for carbon fiber PMCs) out of the basic and applied research categories of the DoD budget (6.1, 6.2, and 6.3A). Defense applications continue to drive the development of PMCs, which are used in an estimated $80 billion of weapons systems.[58]

Reliable PMC structures can now be designed that satisfy all of the engineering requirements of a given application. However, scientific understanding of PMCs has lagged behind engineering practice. To design more efficiently and cost-effectively, and to develop improved materials, it will be necessary to understand and model several important aspects of PMCs. Based on the opportunities outlined above, some research and development priorities for PMCs are suggested below.

Very Important

Processing Science

The primary goal of processing science is to be able to control the fabrication process to ensure complete and uniform cure, minimize thermal stresses, control resin content, and ensure accurate fiber placement. This requires models that can predict the influences of key process variables and techniques for monitoring these variables so that pressure and temperature can be adjusted accordingly. Such models would also provide useful guidelines for tool design. At present, though, modeling is in a very early stage of development.

Table 3-3.—Budgets for Polymer Matrix Composite R&D in Fiscal Years 1985 to 1987 (millions of dollars)

Agency	FY 1985	FY 1986	FY 1987
Department of Defense (6.1, 6.2, 6.3A)	$55.9	$29.2	$33.8
National Aeronautics and Space Administration	23	8.7	5.0
National Science Foundation	1-2	1-2	3.0
National Bureau of Standards	0.4	0.4	0.5
Department of Transportation	—	0.4	0.2
Total	$80-81	$40-41	$42.5

SOURCE: OTA survey of agency representatives

The existence of low-cost fabrication processes will be critical to the use of new PMC systems, such as low-cost, high-performance thermoplastics reinforced with continuous fibers. For instance, methods for fabricating shapes with double curvature are needed. Another important problem is the impregnation and wetting of fiber bundles by these relatively viscous plastics. The effects of processing on microstructure require further study. Similar knowledge is needed of the influence of residual thermal stresses, a particular concern for resins processed at high temperatures. Finally, as for thermosets, process models are required.

Impact Damage

The resistance to impact damage of a PMC structure has a critical effect on its reliability in service. Impact damage barely visible to the naked eye can cause a reduction in strength of as much as 40 percent.[59] Impact resistance is especially important in primary aircraft structures and other safety-critical components. Tougher thermoplastic matrix materials promise to improve the impact resistance of aircraft structures now made with epoxy matrices.

The complexity of the impact damage process makes modeling very difficult. However, it would be very desirable to be able to relate the extent of damage to the properties of the matrix, fiber, and interphase, along with factors such as reinforcement form. This would facilitate the development of more reliable materials and structures. In addition, an understanding of impact damage mechanisms would aid in developing protocols for repair of PMC structures, a field that still relies largely on empirical methods.

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[58] Kenneth Foster, Assistant for Materials Policy, Department of Defense, personal communication, August 1986.

[59] Carl Zweben, General Electric Co., "Assessment of the Science Base for Composite Materials," a contractor report prepared for OTA, December 1985.

Delamination

There is a strong body of opinion that delamination is the most critical form of damage in PMC structures (particularly those produced from prepregs). As noted above, impact damage barely visible on the surface can cause dramatic reductions in strength through local delamination. Voids and pores between layers can also pose serious problems to the integrity of the PMC. Delamination may prove to be a problem of increasing severity in the future because of the trend toward higher working strains that tend to accentuate this mode of failure.

Analyses to date have concentrated on crack growth and failure associated with compressive loading. These need to be verified and refined. In addition, the effects of combined loading, resin fracture toughness, reinforcement form, and environment need to be investigated.

Interphase

The interphase has a critical influence on the PMC in that it determines how the reinforcement properties are translated into the properties of the composite structure. The characteristics of this little-studied region merit thorough investigation. The objective would be to develop a body of knowledge that would guide the development of fiber surface treatments, matrices, and fiber coatings that will optimize mechanical properties and provide resistance to environmental degradation.

Important

Strength

The excellent strength properties of PMCs are one of the major reasons for their use. However, as with many properties of PMCs, their heterogeneity makes strength characteristics very complex. This heterogeneity gives rise to failure modes that frequently have no counterpart in homogeneous materials. Even for the simplest PMCs, unidirectional laminates, there is an inadequate understanding of the relationships between axial and transverse loading (parallel and perpendicular to the fiber direction) and failure. In more complex PMCs, containing several fiber orientations and various flaw populations, efforts to model strength have been largely empirical. It will be important in the future to have analytical models for the various failure modes of unidirectional PMCs and laminates that relate strength properties to basic constituent properties.

Fatigue

Fatigue of PMCs is an important design consideration. Fatigue resistance is a major advantage that PMCs enjoy over metals; however, the traditional models for analyzing fatigue in metals do not apply to PMCs. The risks associated with fatigue failure are likely to increase because of the trend toward use of fibers with higher failure strains, plus the desire to use higher design allowables for existing materials.

Ideally, it would be desirable to be able to predict PMC fatigue behavior based on constituent properties. A more realistic near-term objective is to understand fatigue mechanisms, and how they are related to the properties of fibers, matrix, interphase, loading, and environment of the PMC. Important topics that have not received adequate attention are the fatigue properties of the reinforcements and matrix resins, and compression fatigue of unidirectional PMCs. In view of the increasing interest in thermoplastics, fatigue of these materials also deserves study.

Fracture

One of the most important modes of failure in metals is crack propagation. Arising at regions of high stress, such as holes, defects, or other discontinuities, cracks tend to grow under cyclic tensile load. When cracks reach a critical size, they propagate in an unstable manner, causing failure of the part in which they are located. This, in turn, may result in failure of the entire structure. In contrast, failure of PMCs often results from gradual weakening caused by the accumulation of dispersed damages, rather than by propagation of a single crack.

In view of the significant differences in failure modes between metals and PMCs, use of linear elastic fracture mechanics to describe fracture in these complex materials is controversial. It is open to question whether there are unique values of fracture toughness or critical stress intensity that describe the fracture characteristics of PMCs. To develop reliable design methods and improved materials in the future, it will be necessary to develop a body of fracture analysis that is capable of accounting for the more complex failure mechanisms.

Environmental Effects

The environments to which PMCs are subjected can have a significant effect on their properties. Environments known to be especially damaging are those of high temperature and moisture under load, ultraviolet radiation, and some corrosive chemicals. The key need in the environmental area is to develop a thorough understanding of degradation mechanisms for fibers, resins, and interphases in the environments of greatest concern. This knowledge will lead to more reliable use of existing materials and provide the information required to develop new, more degradation-resistant ones.

Reinforcement Forms and Hybrid PMCs

There are two main reasons for the interest in new reinforcement forms: improved through-the-thickness properties, and lower cost. A pervasive weakness of PMC laminates of all kinds is that the out-of-plane strength and stiffness, being dependent primarily on the matrix, are much inferior to the in-plane properties. This is because in conventional laminates there is no fiber reinforcement in the thickness direction.

New reinforcement forms under development include triaxial fabrics, multilayer fabrics, two-dimensional braids, three-dimensional braids, and various kinds of knits. In addition, laminates have been reinforced in the thickness direction by stitching. From an analytical standpoint, the major drawback to fabrics, braids, and knits is that they introduce fiber curvature that can cause significant loss of strength compared to a unidirectional laminate. However, multidirectional reinforcement appears to confer increased fracture toughness on the PMC.

Use of several types of fibers to reinforce PMCs will be driven by the desire to obtain properties that cannot be achieved with a single fiber, and to reduce cost. For instance, glass fibers, which are cheap but have a relatively low tensile stiffness, can be mixed with more costly, high-stiffness graphite fibers to achieve a PMC that is both stiff and relatively cheap.

With both new reinforcement forms and hybrid reinforcement, there is a great need for analytical methods to identify the configurations required to produce desired properties. Without such tools, it will be necessary to rely on human intuition and time-consuming, costly empirical approaches.

Desirable

Creep Fracture

Materials subjected to sustained loading fail at stress levels lower than their static strengths. This phenomenon is called creep fracture. Topics that require study include tensile and compressive loading of both unidirectional PMCs and laminates, and the influence of temperature and environment. Because the time-dependent degradation of the matrix and interphase properties are typically greater than those of the fiber reinforcements, particular attention should be paid to transverse matrix cracking and delamination.

Viscoelastic and Creep Properties

The occurrence of significant deformation resulting from sustained loading can have an adverse effect on structural performance in some applications, such as reciprocating equipment, bridges, and buildings. Consequently, creep behavior is an important material characteristic. This subject could benefit from development of a database for creep properties of various fibers, matrices, and PMCs, especially for compressive loading, which has received relatively little attention.

Chapter 4

Metal Matrix Composites

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Chapter 4

Metal Matrix Composites

FINDINGS

Metal matrix composites (MMCs) usually consist of a low-density metal, such as aluminum or magnesium, reinforced with particulates or fibers of a ceramic material, such as silicon carbide or graphite. Compared with unreinforced metals, MMCs offer higher specific strength and stiffness, higher operating temperature, and greater wear resistance, as well as the opportunity to tailor these properties for a particular application.

However, MMCs also have some disadvantages compared with metals. Chief among these are the higher cost of fabrication for high-performance MMCs, and lower ductility and toughness. Presently, MMCs tend to cluster around two extreme types. One consists of very high performance composites reinforced with expensive continuous fibers and requiring expensive processing methods. The other consists of relatively low-cost and low-performance composites reinforced with relatively inexpensive particulates or fibers. The cost of the first type is too high for any but military or space applications, whereas the cost/benefit advantages of the second type over unreinforced metal alloys remain in doubt.

Current Applications and Market Opportunities

Current markets for MMCs are primarily in military and aerospace applications. Experimental MMC components have been developed for use in aircraft, satellites, jet engines, missiles, and the National Aeronautics and Space Administration (NASA) space shuttle. The first production application of a particulate-reinforced MMC in the United States is a set of covers for a missile guidance system.

The most important commercial application to date is the MMC diesel engine piston made by Toyota. This composite piston offers better wear resistance and high-temperature strength than the cast iron piston it replaced. It is estimated that 300,000 such pistons are produced and sold in Japan annually. This development is very important because it demonstrates that MMCs are at least not prohibitively expensive for a very cost sensitive application. Other commercial applications include cutting tools and circuit-breaker contacts.

Longer Term Applications

Metal matrix composites with high specific stiffness and strength could be used in applications in which saving weight is an important factor. Included in this category are robots, high-speed machinery, and high-speed rotating shafts for ships or land vehicles. Good wear resistance, along with high specific strength, also favors MMC use in automotive engine and brake parts. Tailorable coefficient of thermal expansion and thermal conductivity make them good candidates for lasers, precision machinery, and electronic packaging. However, the current level of development effort appears to be inadequate to bring about commercialization of any of these in the next 5 years, with the possible exception of diesel engine pistons.

Based on information now in the public domain, the following military applications for MMCs appear attractive: high-temperature fighter aircraft engines and structures; high-temperature missile structures; and spacecraft structures. Testing of a National Aerospace Plane (NASP) prototype is scheduled for the early to mid 1990s, which might be too early to include MMCs. However, it may be possible to incorporate MMCs in the structure or engines of the production vehicle.

Research and Development Priorities

MMCs are just beginning to be used in production applications. In order to make present materials more commercially attractive, and to develop better materials, the following research and development priorities should receive attention:

- *Cheaper Processes*: To develop low-cost, highly reliable manufacturing processes, research should concentrate on optimizing and evaluating processes such as plasma spraying, powder metallurgy processes, modified casting techniques, liquid metal infiltration and diffusion bonding.
- *Cheaper Materials*: Development of lower cost fiber reinforcements is a major need. Continued development work on existing materials is important to lower costs as well.
- *Coatings*: Research in the area of reinforcement/matrix interface coatings is necessary. These coatings can prevent deleterious chemical reactions between matrix and reinforcement which weaken the composite, particularly at high temperature, and optimize the interfacial fiber/matrix bond.

INTRODUCTION

Metal matrix composites (MMCs) generally consist of lightweight metal alloys of aluminum, magnesium, or titanium, reinforced with ceramic particulates, whiskers, or fibers.[1] The reinforcement is very important because it determines the mechanical properties, cost, and performance of a given composite.

Composites reinforced with particulates (discontinuous types of reinforcement) can have costs comparable to unreinforced metals, with significantly better hardness, and somewhat better stiffness and strength. Continuous reinforcement (long fiber or wire reinforcement) can result in dramatic improvements in MMC properties, but costs remain high. Continuously and discontinuously reinforced MMCs have very different applications, and will be treated separately throughout this chapter.

Tailorability is a key advantage of all types of composites, but is particularly so in the case of MMCs. MMCs can be designed to fulfill requirements that no other materials, including other advanced materials, can achieve. There are a number of niche applications in aerospace structures and electronics that capitalize on this advantage.

PROPERTIES OF METAL MATRIX COMPOSITES

There are considerable differences in published property data for MMCs. This is partly due to the fact that there are no industry standards for MMCs, as there are for metals. Reinforcements and composites are typically made by proprietary processes, and, as a consequence, the properties of materials having the same nominal composition can be radically different. The issue is further clouded by the fact that many reinforcements and MMCs are still in the developmental stage, and are continually being refined. Numerous test methods are used throughout the industry, and it is widely recognized that this is a major source of differences in reported properties.[2] Property data given in this chapter are therefore given as ranges rather than as single values.

Some MMC properties cannot be measured as they would be for monolithic metals. For instance, toughness is an important but hard-to-define material property. Standard fracture mechanics tests and analytical methods for metals are based on the assumption of self-similar crack extension; i.e., a crack will simply lengthen without changing shape. Composites, however, are nonhomogeneous materials with complex internal damage patterns. As a result, the applicability of conventional fracture mechanics to MMCs is controversial, especially for fiber-reinforced materials.

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[1] As used in this chapter, the terms "aluminum," "magnesium," and "titanium" denote alloys of these materials used as matrix metals.

[2] Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

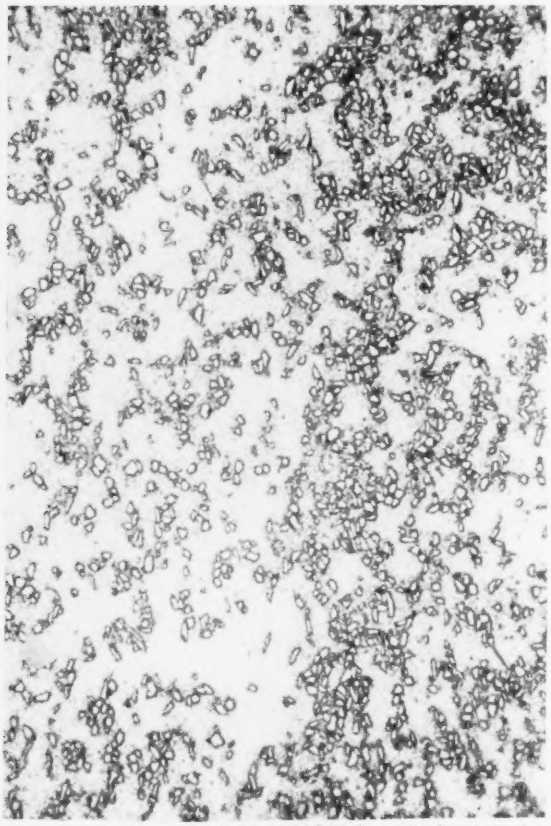

Photo credit: DWA Composite Specialties, Inc.

Micrograph (75 × magnification) of 20 percent volume fraction silicon carbide particulate-reinforced 2124 aluminum.

Discontinuous Reinforcement

There are two types of discontinuous reinforcement for MMCs: particulates and whiskers. The most common types of particulates are alumina, boron carbide, silicon carbide, titanium carbide, and tungsten carbide. The most common type of whisker is silicon carbide, but whiskers of alumina and silicon nitride have also been produced. Whiskers generally cost more than particulates, as seen in table 4-1. For instance, silicon carbide whiskers cost $95 per pound, whereas silicon carbide particulate costs $3 per pound. Cost projections show that although this difference will decrease as production volumes increase, particulates will always have a cost advantage.[3]

Table 4-1.—Costs of a Representative Sample of MMC Reinforcements

Reinforcement	Price ($/pound)
Alumina-silica fiber	1
Silicon carbide particulate	3[a]
Silicon carbide whisker	95
Alumina fiber (FP)	200
Boron fiber	$262
Graphite fiber (P-100)	950[a]

Higher performance reinforcementss (e.g., graphite and boron fibers) have significantly higher costs as well.

[a] Joseph Dolowy, personal communication, DWA Composite Specialties, Inc., July 1987.

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987

In terms of tailorability, a very important advantage in MMC applications, particulate reinforcement offers various desirable properties. Boron carbide and silicon carbide, for instance, are widely used, inexpensive, commercial abrasives that can offer good wear resistance as well as high specific stiffness. Titanium carbide offers a high melting point and chemical inertness which are desirable properties for processing and stability in use. Tungsten carbide has high strength and hardness at high temperature.

In composites, a general rule is that mechanical properties such as strength and stiffness tend to increase as reinforcement length increases.[4] Particulates can be considered to be the limit of short fibers. Particulate-reinforced composites are isotropic, having the same mechanical properties in all directions.

In principle, whiskers should confer superior properties because of their higher aspect ratio (length divided by diameter). However, whiskers are brittle and tend to break up into shorter lengths during processing. This reduces their reinforcement efficiency, and makes the much higher cost of whisker reinforcement hard to justify. Development of improved processing techniques could produce whisker-reinforced MMCs with mechanical properties superior to those made from particulates.

Another disadvantage of using whisker reinforcement is that whiskers tend to become oriented by some processes, such as rolling and extrusion, producing composites with different properties in different directions (anisotropy).[5]

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[3] Ibid.

[4] Ibid.

[5] See the discussion on anisotropy in ch. 3 on Polymer Matrix Composites.

Anisotropy can be a desirable property, but it is a disadvantage if it cannot be controlled precisely in the manufacture of the material. It is also more difficult to pack whiskers than particulates, and thus it is possible to obtain higher reinforcement:matrix ratios (fiber volume fraction, v/o) with particulates. Higher reinforcement percentages lead to better mechanical properties such as higher strength.

Continuous Reinforcement

In fiber reinforcement, by far the most common kind of continuous reinforcement, many types of fibers are used; most of them are carbon or ceramic. Carbon types are referred to as graphite and are based on pitch or polyacrylonitrile (PAN) precursor. Ceramic types include alumina, silica, boron, alumina-silica, alumina-boria-silica, zirconia, magnesia, mullite, boron nitride, titanium diboride, silicon carbide, and boron carbide. All of these fibers are brittle, flaw-sensitive materials. As such, they exhibit the phenomenon of size effect (see ch. 2); i.e., the strength of these fibers decreases as the length increases.

Fiber/matrix interface coatings offer another dimension of tailorability to MMCs. Coatings are very important to the behavior of MMCs to prevent undesirable reactions, improve the strength of the fibers, and tailor the bond strength between fiber and matrix. A reaction barrier is needed for some fiber/matrix combinations, particularly when the composite is exposed to high temperatures in processing or service. For example, boron fiber can be coated with boron carbide and silicon carbide reaction barriers to prevent diffusion and chemical reactions with the matrix that decrease the strength of the composite. Alumina fibers can be given a surface coating of silica to improve tensile strength.

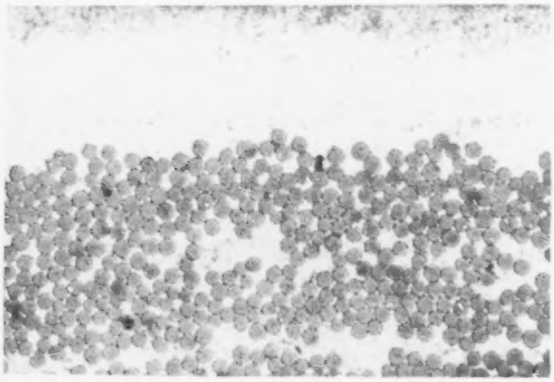

Photo credit: DWA Composite Specialties, Inc.

Cross-section of continuous graphite fiber-reinforced aluminum composite: 52 percent volume fraction fiber, uniaxially reinforced. 300× magnification

Coatings can also be used to tailor the bond strength between fiber and matrix. If adhesion between fiber and matrix is too good, cracks in the matrix propagate right through the fibers, and the composite is brittle. By reducing the bond strength, coatings can enhance crack deflection at the interface, and lead to higher energy absorption during fracture through fiber pullout mechanisms. Sometimes a coating is needed to promote wetting between the matrix and the fiber, and thereby achieve a good bond. Graphite can be coated with titanium diboride in order to promote wetting.

Processing techniques, as well as coatings, can be used to control deleterious fiber/matrix interactions. The application of pressure can be used to force intimate contact between fiber and matrix and thus promote wetting; squeeze casting is one process that does this.

A less common type of continuous reinforcement is wire reinforcement. Wires are made of such metals as titanium, tungsten, molybdenum, beryllium, and stainless steel. Such wires offer some tailorability for certain niche applications; for example, tungsten wire offers good high-temperature creep resistance, which is an advantage in fighter aircraft jet engines and other aerospace applications.

MMC Properties Compared to Other Structural Materials

Table 4-2 compares the most important material properties of MMCs with those of other structural materials discussed in this assessment.

Strength and Stiffness

The stiffnesses and strengths of particulate-reinforced aluminum MMCs are significantly better than those of the aluminum matrix. For example, at a volume fraction of 40 percent silicon carbide particulate reinforcement, the strength is about 65 percent greater than that of the 6061 aluminum matrix, and the stiffness is doubled.[6] Particulate-reinforced MMCs, which are isotropic materials, have lower strength than the axial strength (parallel to the direction of continuous fiber reinforcement) of advanced polymer matrix composites (PMCs), see table 4-2. However, they have much better strength than the transverse strength (perpendicular to the direction of continuous fiber reinforcement) of PMCs. The stiffness of particulate MMCs can be considered to be about the same as that of PMCs.

Unlike particulate-reinforced MMCs and monolithic metals in general, fiber-reinforced MMCs can be highly anisotropic, having different strengths and stiffnesses in different directions. The highest values of strength and stiffness are achieved along the direction of fiber reinforcement. In this direction, strength and stiffness are much higher than in the unreinforced metal, as shown in table 4-2. In fact, the stiffness in the axial direction can be as high as six times that of the matrix material in a graphite fiber/aluminum matrix composite: see table 4-3. However, in the transverse directions, strength values show no improvement over the matrix metal. Transverse strengths and stiffnesses of continuous fiber-reinforced MMCs compared to PMCs are very good, thereby giving MMCs an important advantage over the leading PMCs in structures subject to high transverse stresses.

High values of specific strength and specific stiffness (strength and stiffness divided by density) are desirable for high-strength, low-weight applications such as aircraft structures. Typically, particulate MMCs have somewhat better specific strength and specific stiffness than the matrix metal, and fiber-reinforced MMCs have much better specific strength and specific stiffness than the matrix metal.

Unfortunately, MMCs have a higher density than PMCs, making specific strength and specific stiffness lower than those for PMCs in the axial direction. Transverse specific strength and specific stiffness of MMCs are still better than those of PMCs

High-Temperature Properties

MMCs offer improved elevated-temperature strength and modulus over both PMCs and metals. Reinforcements make it possible to extend the useful temperature range of low density metals such as aluminum, which have limited high-temperature capability (see table 4-2). MMCs typically have higher strength and stiffness than PMCs at 200 to 300° C (342 to 572° F), although development of resins with higher temperature capabilities may be eroding this advantage. No other structural material, however, can compete with ceramics at very high temperature.

Fiber-reinforced MMCs experience matrix/reinforcement interface reactions at high tempera-

Table 4-2.—Structural Properties of Representative MMCs, Compared to Other Materials

Property	Matrix(1)* metal[a]	Particulate(2)* MMC[a]	Fiber(3)* MMC[a]	PMC[b]	Ceramic[b]
Strength (MPa) (axial)	~290	290-480	620-1,240	820-1,680	140-3,900
Stiffness (GPa) (axial)	~70	80-140	130-450	61-224	97-400
Specific strength (axial)	~100	100-170	250-390	630-670	51-670
Specific gravity	2.5-2.8	~2.8	2.5-3.2	1.3-2.5	2.7-5.8
Transverse strength (MPa)	~290	290-480	30-170	11-56	140-3,900
Transverse stiffness (GPa)	Same as axial	Same as axial	34-173	3-12	Same as axial
Maximum use temperature (°C)	180	300	300	260	1,200-1,600
Plane strain fracture toughness (MPa-m$^{1/2}$)	18-35	12-35	—	—	3-9

PMC is used to denote a range of materials including graphite/epoxy, graphite/polyimide, boron/polyimide, and S-glass/epoxy.
Ceramic is used to denote a range of materials including zirconia, silicon carbide, and silicon nitride.
*NOTE: (1) 6061 aluminum.
(2) 6061 aluminum reinforced with 0-40% volume fractions of SiC particulates.
(3) 6061 aluminum reinforced with 50% volume fractions of fibers of graphite, boron, silicon carbide, or alumina.

SOURCES: [a] Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.
[b] "Guide to Selecting Engineered Materials," *Advanced Materials and Processes*, vol. 2, No. 1, June 1987.

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[6] Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

Table 4-3.—Strength and Stiffness of Some Fiber-Reinforced MMCs (Fiber v/o = 50%)

Material Matrix material	Tensile strength (axial) MPa	Tensile strength (transverse) MPa	Stiffness (axial) GPa	Stiffness (transverse) GPa
Aluminum 6061-T6	290	290	70	70
Titanium Ti-6Al-4V	1170	1170	114	114
Composite				
Graphite[a]/aluminum	690	30	450	34
Boron/aluminum	1240	140	205	140
Silicon carbide[b]/ aluminum	1240	100	205	140
Silicon carbide[c]/ aluminum	1040	70	130	99
Alumina[d]/aluminum	620	170	205	140
Silicon carbide[e]/ titanium	1720	340	260	173
Graphite[a]/copper	512	31	464	49

Property improvements of MMCs over unreinforced metals can be significant. For example, the axial stiffness of graphite fiber-reinforced aluminum is roughly 6 times greater than that of the unreinforced aluminum. The axial tensile strength of silicon carbide fiber-reinforced aluminum is about 4 times greater than that of the unreinforced aluminum.

[a] P-120

[b] AVCO monofilament

[c] "Nicalon"

[d] Fiber "FP"

[e] AVCO monofilament

SOURCES: **For all composites except graphite/copper**: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987. **For graphite/copper only**: C. Kaufmann, American Cyanamid, personal communication, Oct. 19, 1987.

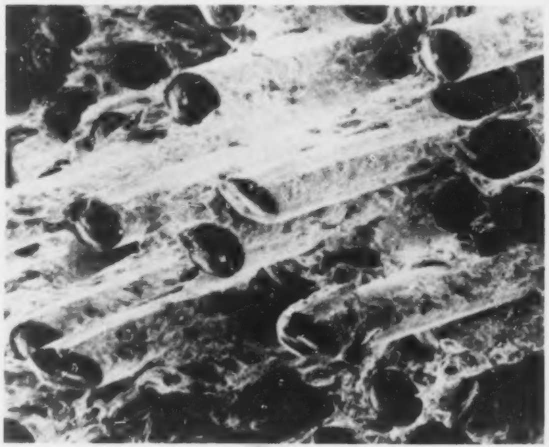

Photo credit: United Technologies Research Center

Fracture surface of boron fiber-reinforced aluminum metal matrix composite.

tures. In addition, the transverse high-temperature strength of fiber-reinforced MMCs is only as good as that of the matrix metal, since mechanical properties in the transverse direction are dominated by the matrix and the fiber/matrix interface. For example, at 320 C (608° F), the axial tensile strength of boron fiber-reinforced aluminum is about 1.1 gigapascals (GPa) compared to only 0.07 GPa for monolithic 6061 aluminum, whereas the transverse strength is 0.08 GPa, about the same as that for the monolithic 6061.[7]

Wear Resistance

Wear resistance of MMCs is excellent compared to that of monolithic metals and PMCs, owing to the presence of the hard ceramic reinforcements. For instance, in one test, the abrasive wear of 2024 aluminum under a 1 kilogram load was shown to be 6 times greater than the wear of the same alloy containing 20 percent volume fraction of silicon carbide whiskers.[8] An alumina-silica fiber-reinforced aluminum piston used in Toyota automobiles demonstrated an 85 percent improvement in wear resistance over the cast iron piston with nickel insert used previously.[9]

Fracture and Toughness

There is a wide variation in fracture toughness among MMCs, although it is generally lower than that of the monolithic metal. Fracture toughness can vary between 65 and 100 percent of the fracture toughness of the monolithic metal alloy.[10] Lower toughness is a trade-off for higher strength and stiffness. Particulate-reinforced MMCs have a lower ultimate tensile strain than the unreinforced metals (see table 4-4) which may be important in some applications. This brittleness can complicate the design process and make joining more difficult as well. Comparison to PMCs is difficult, because the toughness of PMCs is very temperature-dependent.

Thermal Properties

The introduction of silicon carbide particulates into aluminum results in materials having lower coefficients of thermal expansion, a desirable property for some types of applications. By choosing an appropriate composition, the coefficient

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[7] Ibid.

[8] Ibid.

[9] Ibid.

[10] Ibid.

Table 4-4.—Properties of 6061 Aluminum Reinforced With Silicon Carbide Particulate

Reinforcement	Stiffness (GPa)	Tensile strength (MPa)	Tensile strain
0%	10	290	16.0%
10	83	—	7.0
15	86	360	6.5
20	90	430	6.0
25	103	—	3.5
30	117	470	2.0
35	124	—	1.0
40	140	480	0.6

Note the sharp rise in stiffness in the 40% composite (140 GPa) compared to the unreinforced aluminum (10 GPa). Ultimate tensile strength nearly doubles and tensile strain decreases nearly a full order of magnitude.

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

of thermal expansion can be near zero in some MMCs. MMCs also tend to be good heat conductors. Using high thermal conductivity graphite fibers, aluminum-matrix or copper-matrix MMCs can have very high thermal conductivity, compared with other types of composites.

Environmental Behavior

In terms of environmental stability, MMCs have two advantages over PMCs. First, they suffer less water damage than PMCs which can absorb moisture, thereby reducing their high-temperature performance. Second, some MMCs, such as reinforced titanium, can stand high-temperature corrosive environments, unlike PMCs.

Nevertheless, some MMCs are subject to environmental degradation not found in PMCs. For instance, graphite fibers undergo a galvanic reaction with aluminum. This can be a problem when the graphite/aluminum interface is exposed to air or moisture. In addition, PMCs are resistant to attack by many chemicals (e.g., acids) that corrode aluminum, steel, and magnesium.

Cost

A major disadvantage of MMCs compared to most other structural materials is that they are generally more expensive. Both constituent material costs and processing costs are higher. Costs of higher performance reinforcements (mostly fibers) are high, and lower cost reinforcements (mostly particulates) may not yield dramatic improvements in performance. Cost/benefit ratios of most MMCs dictate that they be used only in high-performance applications. However, both

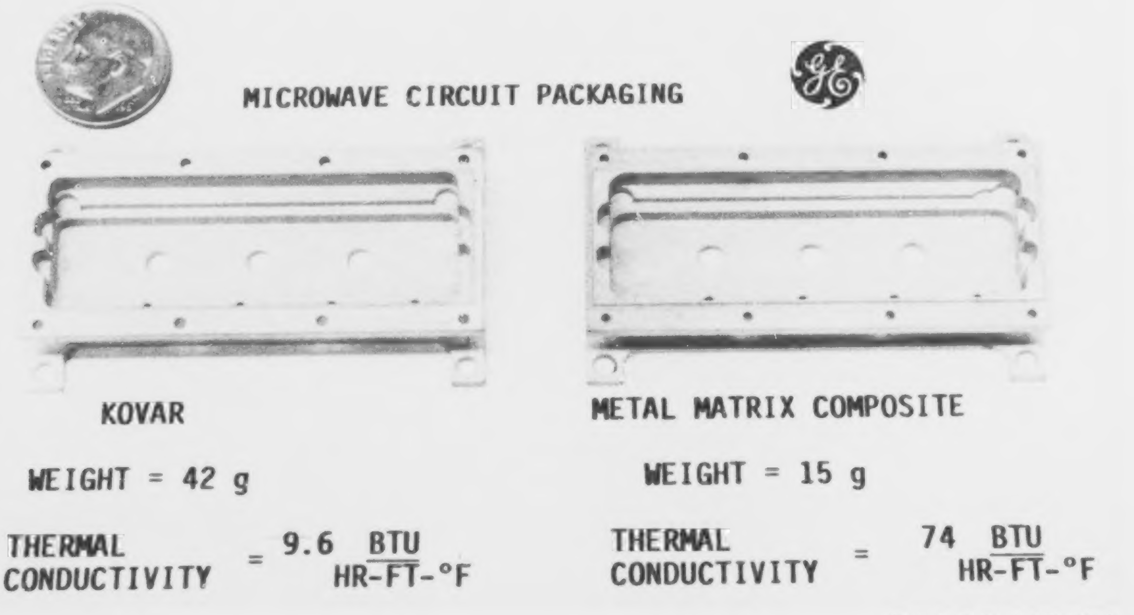
MICROWAVE CIRCUIT PACKAGING
KOVAR
WEIGHT = 42 g
THERMAL CONDUCTIVITY = 9.6 BTU / HR-FT-°F
METAL MATRIX COMPOSITE
WEIGHT = 15 g
THERMAL CONDUCTIVITY = 74 BTU / HR-FT-°F

Photo credit: General Electric Co.

Silicon carbide particle-reinforced aluminum microwave package the material and production costs may drop as more experience is gained in MMC production.

Tailorability of Properties

In some applications, MMCs offer unique combinations of properties that cannot be found in other materials. Electronics packaging for aircraft requires a hard-to-achieve combination of low coefficient of thermal expansion, high thermal conductivity, and low density. Certain MMCs can meet these requirements, replacing beryllium, which is scarce and presents toxicity problems.

Several other examples can be cited to illustrate the unique advantages of MMCs in specialty applications. A large heat transfer coefficient is desirable for space-based radiators; this property is offered by graphite fiber-reinforced copper, aluminum, and titanium (although this latter fiber/matrix combination unfortunately has some interface reaction problems). The higher transverse strengths of MMCs compared to PMCs have led to several MMC space applications, such as the space shuttle orbiter struts, made of boron fiber-reinforced aluminum.

One of the most important applications of MMCs is the Toyota truck diesel engine piston, produced at a rate of about 300,000 pistons per year.[11] This consists of aluminum selectively reinforced in the critical region of the top ring groove with a ring-shaped ceramic fiber preform. (A preform is an assemblage of reinforcements in the shape of the final product that can be infiltrated with the matrix to form a composite.)

Two types of fibers are used: alumina and alumina-silica. Both are relatively low-cost materials originally developed for furnace insulation.

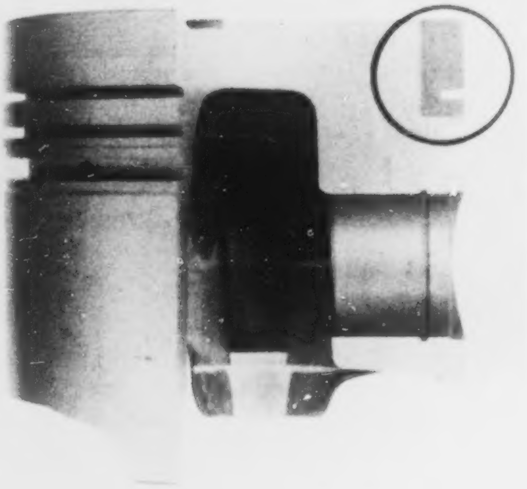

Photo credit: Toyota Motor Corp.

Aluminum diesel engine piston with local fiber reinforcement in ring groove area

Use of local reinforcement to improve wear resistance makes possible the elimination of nickel and cast iron inserts. This reduces piston weight and increases thermal conductivity, improving engine performance and reducing vibration.

This approach minimizes cost and thereby makes MMCs more competitive with cast iron. This design not only offers better wear resistance and better high-temperature strength but also eliminates one type of part failure associated with the design it replaced. It is considered by some to be a development of historic proportions because it demonstrates that MMCs can be reliably mass produced. It also shows that at least one type of aluminum matrix MMC can perform reliably in a very severe environment.

DESIGN, PROCESSING, AND TESTING

In ceramics and polymer matrix composites manufacturing, the material is formed to its final shape as the microstructure of the material is formed. MMCs can be produced in this way, or, as is traditionally done with metals, formed into billets or sheets and later machined to a final shape. Viable, inexpensive near-net-shape techniques for forming MMCs have not been successfully developed as yet, and there is still a debate about on the advantages of producing standard

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[11] Ibid.

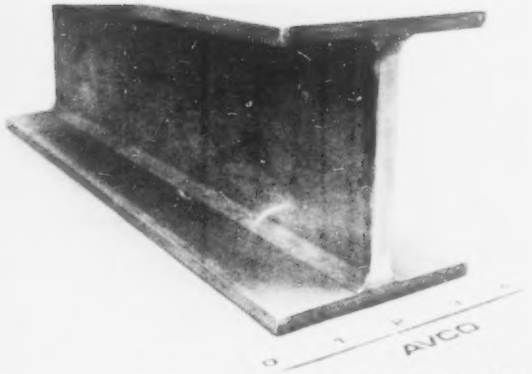

Photo credit: AVCO Corp.

Centrifugal casting of silicon carbide-reinforced aluminum.

shapes to be machined by the purchaser to final form, compared to the custom production of near-net-shape parts. Forming of net-shape MMC parts necessitates close integration of design and manufacture, where production of standard MMC structural shapes does not.

Design

The variability of metal matrix composite properties is a handicap to designing with these materials. There are currently no design aids such as property databases, performance standards, and standard test methods. In addition, most designers are much more familiar with monolithic metals. The lack of experience with MMCs increases the design and manufacturing costs associated with the development of a new product. As with ceramic structures, brittleness is a new and difficult concept to most designers. MMCs are brittle materials, and new methods of design will become important in the development of MMC applications.

Processing

Because MMC technology is hardly beyond the stage of R&D at present, costs for all methods of producing MMCs are still high. Manufacturing methods must ensure good bonding between matrix and reinforcement, and must not result in undesirable matrix/fiber interfacial reactions.

MMC production processes can be divided into primary and secondary processing methods, though these categories are not as distinct as is the case with monolithic metals. Primary processes (those processes used first to form the material) can be broken down into *combining* and *consolidation* operations. Secondary processes can be either *shaping* or *joining* operations. Table 4-5 shows the manufacturing methods discussed here and notes which types of operations are included in each method.

As with ceramics, net-shape methods are very important manufacturing processes. The machining of MMCs is very difficult and costly in that MMCs are very abrasive, and diamond tools are needed. In addition, it is desirable to reduce the amount of scrap left from the machining process because the materials themselves are very expensive.

Continuous Reinforcement[12]

The following discussion covers the primary and secondary processes involved in the manufacture of MMCs with continuous reinforcement.

Primary Processes.—Basic methods of combining and consolidating MMCs include liquid metal infiltration, modified casting processes, and deposition methods such as plasma spraying. Hot pressing consolidates and shapes MMCs. Diffusion bonding consolidates, shapes and joins MMCs. See table 4-6 for selected MMC processing methods and their characteristics.

There is considerably more disagreement on what is the most promising method for processing fiber-reinforced MMCs than there is for processing of particulate-reinforced MMCs. The Toyota diesel engine piston has been heralded as an example of the promise of modified casting techniques for keeping costs down. Critics charge that these types of casting techniques have not proven adequate for manufacturing MMCs with desirable mechanical properties. (The Toyota piston

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[12] As examples in the following discussion of processing, two common types of particulate- and fiber-reinforced composites will be referred to as needed: silicon carbide particulate-reinforced aluminum, and boron fiber-reinforced aluminum.

Table 4-5.—MMC Manufacturing Methods

	Combines	Consolidates	Shapes	Joins
Primary methods:				
Casting Squeeze casting, compocasting, gravity casting, low-pressure casting	X	X	X	
Diffusion bonding		X	X	X
Liquid infiltration Gravity, inert gas pressure, vacuum infiltration	X	X		
Deposition Chemical coating, plasma spraying, chemical vapor deposition, physical vapor deposition, electrochemical plating	X	X		
Powder processing Hot pressing, ball mill mixing, vacuum pressing, extrusion, rolling	X	X	X	
Secondary methods:				
Shaping Forging, extruding, rolling, bending, shearing, spinning, machining		X	X	
Machining Turning, boring, drilling, milling, sawing, grinding, routing, electrical discharge machining chemical milling, electrochemical milling			X	
Forming Press brake, superplastic, creep forming		X	X	X
Bonding Adhesive, diffusion				X
Fastening				X
Soldering, brazing, welding				X

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

uses fiber reinforcement mostly for wear resistance and less for more universally important properties such as strength.) Some industry MMC advocates suggest that processes such as diffusion bonding and plasma spraying are more promising for achieving high performance, and that lower costs will come only with more production experience with these processes.

Secondary Processes.—Machining processes for MMCs reinforced with ceramic materials, which are hard and abrasive, generally are much more expensive than for monolithic structural metals. As a rule, diamond tools are required because carbide and other tools wear out too quickly. Despite this limitation, all of the basic mechanical methods, such as drilling, sawing, milling, and turning have been proven to be effective with MMCs. Electrical discharge machining also has been shown to be effective.

Mechanical fastening methods, such as riveting and bolting have been found to work for continuously-reinforced MMCs. The same is true

Table 4-6.—Selected MMC Processing Techniques and Their Characteristics

Techniques	Characteristics
For fiber-reinforced MMCs:	
Liquid metal infiltration (low pressure)	near-net-shape parts economical high porosity oxidation of matrix and fiber not reliable as yet
Liquid metal infiltration (intert gas pressure, vacuum)	less porosity and oxidation than low pressure techniques
Low pressure casting	near-net-shape parts low cost expensive preforms required three-dimensional preforms are difficult to make
Squeeze casting	good fiber wetting lower porosity expensive molds needed large capacity presses needed
Plasma spraying	potential for lower processing costs
Diffusion bonding	lower temperatures than hot pressing reduces fiber/matrix interactions not capable of net-shape parts except simple shapes slow, expensive fiber damage can occur
Hot Pressing	heats matrix above melt temperature, which can degrade reinforcement
For particulate-reinforced MMCs:	
Powder metallurgy	high volume fractions of particulate are possible (better properties) powders are expensive not for near-net-shape parts
Liquid metal infiltration	net-shape parts can use ingots rather than powders lower volume fraction of particulates (means lower mechanical properties)
Squeeze casting	may offer cost advantage; however molds and presses may be expensive

SOURCE: Carl Zweben, "Metal Matrix Composites," contractor report for OTA, January 1987.

for adhesive bonding. Boron fiber-reinforced aluminum pieces can be metallurgically joined by soldering, brazing, resistance welding and diffusion bonding.

Discontinuous Reinforcement

The following discussion covers the primary and secondary processes involved in the manufacture of MMCs with discontinuous reinforcement.

Primary Processes.—The most common methods for producing particulate- and whisker-reinforced MMCs are powder processing techniques. There has not been much success at producing near-net-shape structures as yet.[13] (See discussion in chapter 2 on the desirability of near-net-shape processing.) Other processes for discontinuously-reinforced MMCs are liquid metal infiltration and casting techniques (see table 4-6).

At this time, there is no one MMC manufacturing method that holds great promise for reduc-

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[13] Zweben, op. cit., January 1987.

Photo credit: AVCO Specialty Materials

Centrifugal casting around braided tube of SiC fibers and yarn.

Photo credit: AVCO Specialty Materials

Diffusion bonded SiC fiber-reinforced titanium: cross section of a hollow turbine blade.

ing costs, although there seems to be some agreement that for particulate-reinforced MMCs, liquid metal infiltration and powder metallurgy techniques are likely candidates for future development.

Secondary Processes.—One of the major advantages of particulate- and whisker-reinforced MMCs is that most of the conventional metalworking processes can be used with minor modifications (see table 4-5). Methods demonstrated include forging, extruding, rolling, bending, shearing, and machining. Although they are expensive, all conventional machining methods have been found to work for these materials, including turning, milling, and grinding.

Photo credit: AVCO Specialty Materials

Silicon carbide fiber-reinforced aluminum shaped by electrical discharge machining.

A wide variety of joining methods can be used including mechanical fastening techniques, metallurgical methods employed with monolithic metals, and adhesive bonding as used for PMCs.

Costs

MMC costs are currently very high, and for them to come down, there must be some standardization and a reliable compilation of materials properties (in a form such as a design database). This can be achieved only through greater production experience with MMC materials. Some experts argue that entirely new materials and processes must be found that are cheaper than the present ones. Opponents of this view hold that development of new processes and materials will delay a decrease in costs of existing materials, because it will take much longer to gain the production experience necessary.

Most present users buy preformed shapes, such as billets, plates, bars and tubes, and then machine these shapes to specification. MMCs are not currently sold in standard sizes; users can order any size, manufactured to order. This lack of standardization keeps prices for shapes high. Some users produce their own MMCs for use inhouse. For example, Lockheed Georgia produces silicon carbide fiber-reinforced aluminum matrix composites for designing, manufacturing and testing fighter aircraft fins.

The cost of an MMC part depends on many factors including shape, type of matrix and reinforcement, reinforcement volume fraction, reinforcement orientation, primary and secondary fabrication methods, tooling costs, and number of parts in the production run. At present, there is little information available on production costs. The only items produced in any quantity are the Toyota engine pistons. Costs for this application are proprietary information, but the costs of these MMCs are at least not prohibitive in a very cost-sensitive product.

Costs are very volume sensitive; high costs keep volumes low, and low volumes mean high costs. Of course, some materials are inherently expensive and will never be cheap enough for widespread commercial use, regardless of volume.

With the exception of alumina-silica discontinuous reinforcement fibers, reinforcement prices are orders of magnitude higher than those of metals used in mass production items such as automobiles. Unfortunately, the stiffness of alumina-silica fibers is not substantially greater than that of aluminum. The room-temperature strength of aluminum reinforced with these fibers also shows little or no improvement over monolithic aluminum, although wear resistance and elevated-temperature strength are enhanced. The significance of this is that the fibers that provide major improvements in material properties are quite expensive, while use of low-cost alumina-silica fibers provides only modest gains in strength and stiffness.

Testing

Unlike monolithic metals, in which the main types of flaws are cracks, porosity, and inclusions, composites are complex, heterogeneous materials that are susceptible to more kinds of flaws, including delamination, fiber misalignment, and fiber fracture.

Failure in monolithic metals occurs primarily by crack propagation. The analytical tool called linear elastic fracture mechanics (LEFM) is used to predict the stress levels at which cracks in metals will propagate unstably, causing failure. Failure modes in composites, especially those reinforced with fibers or whiskers, are far more complex, and there are no verified analytical methods to predict failure stress levels associated with observed defects. As a consequence, empirical methods have to be used to evaluate how critical a given flaw is in an MMC.

Two basic methods have been established as reliable flaw-detection techniques for MMCs: radiography and ultrasonic C-scan. Radiography, useful only for thin panels, detects fiber misalignment and fractures. C-scan identifies delaminations and voids. There are no existing nondestructive evaluation (NDE) methods for reinforcement degradation in MMCs.

The costs of NDE methods for MMCs should be no greater than for monolithic metals. However, the reliability of manufacturing processes for these materials has not been established and MMCs cannot be reliably or repeatably produced as yet. Because fabrication processes are not dependable at present, it is generally necessary to use NDE for MMCs in cases where testing would not be employed at all, or as extensively, for monolithic metals. This additional cost factor should decrease as experience and confidence are gained with MMCs.

HEALTH AND SAFETY

There is little documentation as yet of safe handling and machining practices for MMCs. Materials handling practices are given by materials safety data sheets, and few yet exist for MMCs. However, there is one materials safety data sheet that applies to the MMC production process of plasma spraying.[14]

Health hazards associated with MMCs are similar to those found in the production of ceramics and PMCs. As with ceramics the most serious health hazard is associated with the possible carcinogenic effects of ceramic fibers due to their size and shape. MMC reinforcement fibers falling in this category include alumina, alumina-silica, graphite, boron carbide, and alumina-boria-silica. The effects of ceramic fibers on humans are largely unknown. Until such data become available, the indications discussed in chapter 2 for ceramics also apply to the manufacture of MMCs reinforced with these fibers.

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[14] Robert Buffenbarger, International Association of Machinists and Aerospace Workers, personal communication, March 23, 1987.

APPLICATIONS

There are very few commercial applications of MMCs at the present time. Industry observers believe that the level of development effort in the United States is not large enough to lead to significant near-term commercial use of MMCs. However, the Toyota truck diesel engine piston has spurred the major U.S. automakers to undertake preliminary activity in MMCs. Although considerable interest in these materials is being generated in the United States, it will be decades before they are likely to have an appreciable impact on production levels of competing materials.

MMCs are not competing solely with monolithic metals; they are also competing with the whole range of advanced materials, including PMCs, ceramics, and other new metal alloys. It is not yet clear whether, compared to PMCs, ceramics, and monolithic metals, MMCs will have big enough performance advantages to warrant use in a wide variety of applications. In fact, MMCs may be limited to niche applications in which the combinations of properties required cannot be satisfied by other structural materials.

The properties that make MMCs attractive are high strength and stiffness, good wear resistance, and tailorable coefficient of thermal expansion and thermal conductivity. Furthermore, development of high-temperature MMCs has been cited as a way to help reduce U.S. dependence on critical and strategic materials, such as manganese and cobalt.[15] The following sections describe the current and future applications for which these properties are of value.

Current Applications

Current MMC markets in the United States are primarily military. MMCs have potential for use in aircraft structures, aircraft engines, and naval weapons systems. Experimental MMC components were first developed for applications in aircraft, jet engines, rockets, and the space shuttle. There has been little government funding of MMCs for commercial applications in the United States, and only a small number of specialized applications have been developed by private industry.

Military/Space

The high stiffness and compression strength and low density of boron fiber-reinforced aluminum led to its use in production space shuttle orbiter struts. Its high cost has prevented wider use.

The National Aeronautics and Space Administration (NASA) Hubble Space Telescope uses two antenna masts made of aluminum reinforced with P-100 pitch-based graphite fibers. This material was selected because of its high specific stiffness and low coefficient of thermal expansion.[16] This material replaced a dimensionally stable telescope mount and an aluminum waveguide, resulting in a 70 percent weight savings.[17]

Two companies are producing silicon carbide particulate-reinforced aluminum instrument covers for a missile guidance system. This is the first production application of particulate-reinforced MMCs in the United States.

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[15] Zweben, op. cit., January 1987

[16] Ibid.

[17] William C. Riley, Research Opportunites, Inc., personal communication, October 27, 1987.

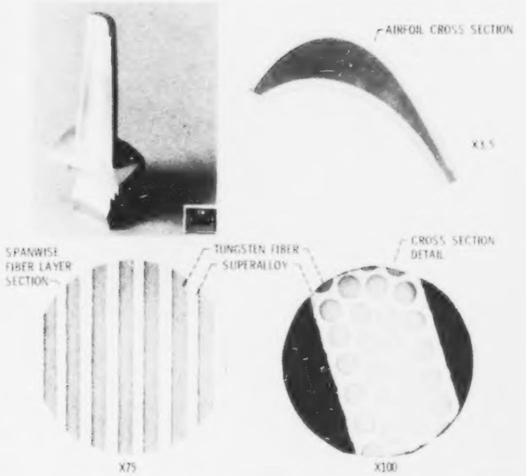

Photo credit: NASA Lewis Research Center

Tungsten wire-reinforced super alloy gas turbine engine blade

Commercial

The Toyota piston has stimulated a considerable interest in MMCs for pistons and other automotive parts on a worldwide basis. Other components now being evaluated by automakers world-wide include connecting rods, cam followers, cylinder liners, brake parts, and drive shafts.

Experimental MMC bearings have been tested on railroad cars in the United Kingdom. An experimental material for electronic applications has been developed in Japan, consisting of copper reinforced with graphite fiber. Another electrical use of MMCs is in circuit breakers. Graphite-reinforced copper used as a "compliant layer" minimizes thermal stresses in an experimental magnetohydrodynamic (MHD) generator ceramic channel in Japan. An aluminum tennis racket selectively reinforced with boron fiber was sold commercially in the United States for a brief time during the 1970s.

Future Applications

Future applications include those which could be possible in the next 5 to 15 years.

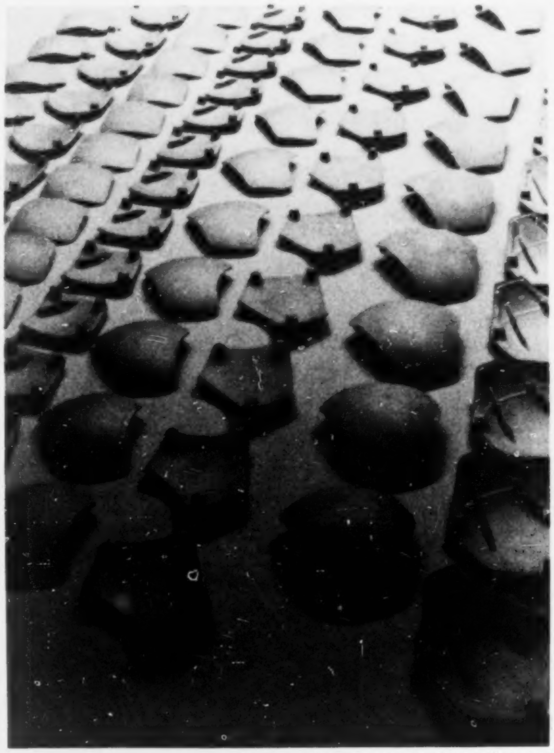

Photo credit: Advanced Composite Materials

Missile guidance system covers of silicon carbide particle-reinforced aluminum.

Military/Space

Based on information in the public domain, the following applications appear likely to be developed in the United States: high-temperature fighter aircraft engines and structures, high-temperature missile structures, spacecraft structures, high-speed mechanical systems, and electronic packaging.

Development of applications such as hypersonic aircraft, which will require efficient high-temperature structural materials, will undoubtedly lead to increasing interest in MMCs.

Commercial

Commercial applications in the next 5 years are likely to be limited to diesel engine pistons, and perhaps sporting goods such as golf clubs, tennis rackets, skis, and fishing poles. There are a number of potential applications that are technically possible but for which the current level of development effort is inadequate to bring about commercialization in the next 5 years; these include: brake components, push rods, rocker arms, machinery and robot components, computer equipment, prosthetics, and electronic packaging.

High Specific Stiffness and Strength.—MMC materials with high specific stiffness and strength are likely to have special merit in applications in which weight will be a critical factor. Included in this category are land-based vehicles, aircraft, ships, machinery in which parts experience high accelerations and decelerations, high-speed shafts and rotating devices subject to strong centrifugal forces.

The high value of weight in aircraft makes use of MMCs a strong possibility for structural applications, as well as for engine and other mechanical system components. Mechanical properties of MMCs could be important for a number of medical applications, including replacement joints, bone splices, prosthetics, and wheelchairs.

There are numerous industrial machinery components that could benefit from the superior specific strength and stiffness of MMCs. For example, high-speed packaging machines typically have reciprocating parts. Some types of high-speed machine tools have been developed to the point where the limiting factor is the mass of the assemblies holding the cutting or grinding tools, which experience rapid accelerations and decelerations. Further productivity improvements will require materials with higher specific mechanical properties. Computer peripheral equipment, such as printers, tape drives, and magnetic disk devices commonly have components that must move rapidly. MMCs are well suited for such parts.

The excellent mechanical properties of MMCs make them prime candidates for future application in robots, in which the weight and inertia of the components have a major effect on performance and load capacity. Centrifugal forces are a major design consideration in high-speed rotating equipment, such as centrifuges, generators, and turbines. As these forces are directly proportional to the mass of the rotating components, use of materials with high specific properties - MMCs - will be a way of achieving future performance goals.

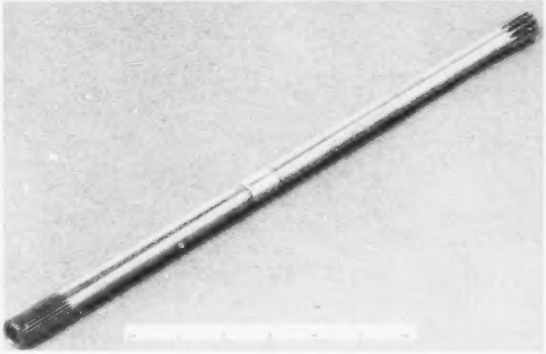

Photo credit: AVCO Specialty Materials

Drive shaft hot molded of silicon carbide fiber-reinforced aluminum.

For high-speed rotating shafts, such as automobile and truck drive shafts, a major design consideration is that the rotational speed at which the shaft starts to vibrate unstably, called the critical speed, must be higher than the operating speed. As critical speed depends on the ratio of stiffness to density, the high specific stiffness of MMCs makes them attractive candidates for this application.

Attractive Thermal Properties.—There are a number of potential future applications for which the unique combinations of physical properties of MMCs will be advantageous. For example, the special needs of electronic components present particularly attractive opportunities.

Electronic devices use many ceramic and ceramic-like materials, that are brittle and have low coefficients of thermal expansion (CTEs). Examples are ceramic substrates such as alumina and beryllia, and semiconductors such as silicon and gallium arsenide. These components frequently are housed in small, metallic packages. MMCs can help prevent fracture of the components or failure of the solder or adhesive used to mount these components, since the CTE of the package can be tailored to match that of the device.

Another desirable feature of packaging materials is high thermal conductivity to dissipate heat generated in the system, since the reliability of electronic chips decreases as operating temperature increases. Two of the more common metals now used in packaging are molybdenum and Kovar, a nickel-iron alloy. The thermal conductivity of Kovar is quite low, only about 5 percent of that of copper, and it cannot be used in applications in which large amounts of heat must be dissipated. Molybdenum, which is more expensive and difficult to machine, is normally used in such cases. MMCs (e.g., with a high thermal conductivity copper matrix) could be used instead of these two materials. Examples of potential future applications include heat sinks, power semiconductor electrodes, and microwave carriers.

The low CTE that can be achieved with some MMCs makes them attractive for use in precision machinery that undergoes significant temperature change. For example, machines that assemble precision devices are commonly aligned when cold. After the machines warm up, thermal expansion frequently causes them to go out of alignment. This results in defective parts and down time required for realignment. Laser devices, which require extremely stable cavity lengths, are another potential application for which low CTE is an advantage.

Markets

Market projections for MMCs vary widely. One market forecast by C. H. Kline is that MMCs will play no significant role in the current advanced composite markets until after 1995.[18] A second forecast (Technomic Consultants) is that U.S. nonmilitary uses of MMCs will reach $100 million per year by 1994, and world-wide commercial uses will reach $2 billion per year.[19]

There does seem to be agreement though, that in the United States, MMC materials are likely to be used primarily in military and space applications, and, to a much smaller degree, in electronic and automotive applications. Because MMC materials are currently used mainly for research purposes, the markets for them are now only a few thousand pounds per year.[20] Materials costs should decrease with time, as production volumes increase. However, the actual downward trend has been slower than most predictions, and the cost/performance benefits of MMCs have yet to be demonstrated over alternative materials in large volume applications.

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[18] Jacques Shouttens, Metal Matrix Composites Information Analysis Center (MMCIAC), personal communication, March 27, 1987.

[19] Ibid.

[20] Ibid.

RESEARCH AND DEVELOPMENT PRIORITIES

Federal funding of MMC research and development (R&D) comes mainly from the military. Combined totals for the three services plus the Defense Advanced Research Projects Agency (DARPA) for 6.1, 6.2, and 6.3A money were $29.7 million for fiscal year 1987.[21] There are a number of classified projects, and projects in other categories of funds, that also involve MMCs. Although the Department of Defense is the major government funding source, NASA also funds MMC research. NASA plans to provide $8.6 million for MMCs in fiscal year 1988, up from $5.6 million in fiscal year 1987.[22]

The following section describes R&D priorities for MMCs in three broad categories of descending priority. These categories reflect a consensus as determined by OTA of research that needs to be done in order to promote the development of these materials.

Very Important

Cheaper Processes

First in importance is the need for low-cost, highly-reliable manufacturing processes. Several industry experts advocate emphasis on modified casting processes; others suggest diffusion bonding and liquid metal infiltration as likely candidates for production of fiber-reinforced MMCs.

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[21] Jerome Persh, Department of Defense, personal communication, August 1987.

[22] Brian Quigley, National Aeronautics and Space Administration, personal communication, December 1987.

There is some agreement that plasma spraying is also a promising method. For particulate-reinforced MMCs, powder metallurgy and liquid infiltration techniques are considered most promising. To develop near-term applications, research should concentrate on optimizing and evaluating these processes, including development of low-cost preforms.

Cheaper Materials

Development of high-strength fiber reinforcements of significantly lower cost is a major need, as there are no high-performance, low-cost fibers available at present. There are two schools of thought as to the best approach to reducing costs. Some analysts believe that the range of usefulness can be expanded by the development of new fibers with better all-purpose design properties, such as higher strength, higher temperature, and lower cost; they also see new matrix alloys as important to facilitate processing and to optimize MMC performance. However, some critics charge that this search for all-purpose fibers and better matrices is likely to be unrewarding and that increased production experience with present fibers and matrices is the best route to lower costs, particularly for potential near-term applications.

Interphase

Control over the fiber/matrix interphase in MMCs is critical to both the cost and performance of these materials. For example, new fiber coatings are needed to permit a single fiber to be used with a variety of matrices. This would be cheaper than developing a new fiber for each matrix.

At high temperatures, fiber/matrix interactions can seriously degrade MMC strength. Research in the area of coatings is desirable, not only to prevent these deleterious reactions but also to promote the proper degree of wetting to form a good fiber/matrix bond. Coatings add to the material and processing costs of MMCs, so that research into cheaper coatings and processes is essential.

Important

Environmental Behavior

It is critical to understand how reinforcements and matrices interact, particularly at high temperatures, both during fabrication and in service. A thorough understanding of material behavior is necessary to ensure reliable use and to provide guidelines for development of materials with improved properties. To date, study of the behavior of MMCs in deleterious environments has been much more limited than for PMCs. Research is needed in the areas of stress/temperature/deformation relations, strength, mechanical and thermal fatigue, impact, fracture, creep rupture, and wear.

Fracture

The subject of fracture behavior in MMCs deserves special attention. The applicability of traditional analytical techniques is controversial because MMCs are strongly heterogeneous materials. It seems reasonable that these traditional techniques should be valid at least for particulate-reinforced MMCs, because they do not appear to have the complex internal failure modes associated with fiber-reinforced MMCs. In view of the lack of agreement on how to characterize fracture behavior of MMCs, though, it will be necessary to rely on empirical methods until a clearer picture emerges.

Nondestructive Evaluation

Reliable NDE techniques must be developed for MMCs. They should include techniques for detecting flaws and analytical methods to evaluate the significance of these flaws. In MMCs as in PMCs, there is the possibility of many kinds of flaws, including delamination, fiber misalignment, and fracture. There are no NDE procedures presently available for measuring the extent of undesirable reinforcement/matrix interaction and resultant property degradation.

Machining

The machining of MMCs is currently a very expensive process that requires diamond tools because of the materials' very hard and abrasive ceramic reinforcements. As machining is a major cost factor, development of improved methods tailored to the unique properties of MMCs would help to make these materials more competitive.

Desirable

Modeling

Analytical modeling methods would be of value in helping to develop and optimize processes for fabricating MMCs. What are needed are design methods that take into account plasticity effects and provide for development of efficient, selectively reinforced structures and mechanical components. Research on modeling of processing behavior is necessary, together with the eventual development of databases of properties and process parameters.

Chapter 5

Factors Affecting the Use of Advanced Materials

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Chapter 5

Factors Affecting the Use of Advanced Materials

FINDINGS

Because of the intimate relationship between advanced materials and structures produced from them, the design and manufacture of these new materials must be treated as an integrated process. These materials make it possible to form parts and systems in larger, more combined operations than are possible with traditional metals technology. One operation can form both the part and the material, thereby eliminating costly assembly operations. The need for such an integrated, or unified, approach will affect all aspects of manufacturing.

Costs

Although the high per-pound cost is currently a barrier to the increased use of advanced structural materials, low cost could become a selling point for these materials in the future if systems costs are considered. Advanced structural materials offer the opportunity to consolidate parts and reduce manufacturing and assembly costs. In general, use of advanced materials will only be cost-effective if the manufacturer can offset higher raw materials costs with savings in assembly and maintenance costs.

Multidisciplinary Approach

The integrated nature of advanced materials manufacturing will require close cooperation between research scientists, designers and production engineers. Effective commercialization will require teams that bring together expertise from many professional disciplines.

Education and Training

Cooperation and blending across different disciplines in industry will require interdepartmental educational opportunities for students in universities. At the same time there is a need for skilled engineers who have strong backgrounds in these advanced materials. Retraining will be required for engineers already in the work force, and training in manufacturing with these materials will be needed for production workers.

Standards

Several types of standards will facilitate integrated design with advanced materials: quality control standards applied at each stage of the manufacturing process, product specification standards, and standardized test methods for materials qualification. Numerous groups in the United States are working on domestic materials standards, although progress has been slow. There is also a large domestic effort on the part of the Japanese. Several international organizations are also attempting to develop international standards for advanced materials.

Automation

Those forms of automation that aid the integration of design and manufacturing will be of great use in speeding up the acceptance of the new materials. These might include design databases, automated processing equipment and sensors for process information feedback. Automation can help reduce material and process cost, ensure part quality, and eliminate the long manufacturing times inherent in some processes.

Technical challenges for the automation of advanced materials production are generally similar to those for traditional metals production; however, such problems as the lack of design data and strict quality control requirements may be more serious for advanced composite or ceramic part production. Automation will proceed slowly, given the newness of the materials and the time needed to develop experience with, and confidence in, their use.

INTRODUCTION

The future of advanced materials involves more than purely technical changes. Other factors that will affect the development and commercialization of these materials are: an integrated approach to design and manufacturing, a systems approach to cost, interdisciplinary research and production, education and training, standards development, and automation of design and manufacturing processes.

Because advanced ceramics and composites are tailored to suit their applications, these materials cannot be considered apart from the structures made from them. Both material and structure are manufactured together in an integrated fabrication process. This is fundamentally different from the sequential manufacturing processes associated with conventional materials. With metals, the materials and processes are determined by the specifications; with advanced materials, the materials and manufacturing processes are designed with the aid of the specifications.

The principle of integration will have a strong influence on the future use of advanced materials. This development will depend on more unified approaches to problem solving, requiring a broader view on a wide range of issues. An integrated approach will be imperative, not just in finding solutions to technical challenges, but also in dealing with various institutional and economic issues.

INTEGRATED DESIGN

When designing a structure to be made of metal, the design team specifies the metal to be used and has a rough idea of its final properties. This team then can simply hand the design over to the production team. The production team, in separate operations and without further contact with the designers, treats the metal to achieve the microstructure and mechanical properties that the designers envisioned, shapes the structure in a rough fashion, and finishes it to have the precise shape desired.

With advanced composites and ceramics, these steps are collapsed into a single processing step; thus a design team working with these materials cannot be separated from the manufacturers of the part. Design of the material, structure, and manufacturing process is called integrated design.

Integrated design requires a large amount of data. Some of the kinds of materials property information a designer might want are shown in table 5-1. Mechanical properties of ceramic and composite structures, as well as of the constituent materials, will be needed for a wide variety of materials. Processing parameter data and cost data will also be important in material and process choice.

Table 5-1.—Polymer Matrix Composite Design Parameters

1. Tensile strength x,y
2. Tensile stiffnesses x,y
3. Elongation at break x,y
4. Flexural strength
5. Flexural stiffnesses
6. Compressive strength x,y
7. Compressive stiffnesses x,y
8. Shear strength (short beam shear test and/or off-axis tensile test)
9. Shear stiffnesses x,y
10. Interlaminar strength (G_C)
11. Impact strength
12. Compression strength after impact
13. Coefficient of thermal expansion x,y
14. Hygroscopic expansion (moisture coefficient x,y)
15. Poisson's ratios x,y
16. Fiber volume content
17. Void content
18. Density

x,y: In two directions, parallel and perpendicular to the long direction of the reinforcement fiber.

NOTE: These design parameters are a few of the large number of design parameters which give rise to the plethora of variables which must be controlled during manufacturing.

SOURCE: Materials Modeling Associates, "Properties, Costs, and Applications of Polymeric Composites," contractor report for OTA, December 1985.

There is currently a great deal of effort underway by many different groups to determine what might comprise a materials design database for PMCs. (Ceramic and metal matrix composite

[MMC] technologies are less evolved and may not be ready at this time for database development.) Ideally this data should be available for a wide range of fibers and matrices. A comparison of the costs of different materials would also be a desirable feature of such a materials database.

To direct the manufacture of a part, or to be able to design a part with forethought on how it could be manufactured, processing variables databases would also be necessary. These databases would include variables such as curing times of resins and heat treatment curves for obtaining various microstructures, and, most notably, processing costs. A processing database would be of greatest benefit in deriving properties of a composite or ceramic *structure* as a whole. Having this knowledge could allow custom tailoring of parts, and may trim costs through reducing tendencies to overdesign and through shortening design time.

Several attempts are being made to establish databases for advanced materials. The National Bureau of Standards is currently attempting to develop a protocol for an electronic database for ceramic materials. In the private sector, one effort underway to create a centralized database is the National Materials Properties Data Network, which plans to provide its subscribers with the capability to search electronically a large number of data sources that have been evaluated by experts.[1]

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[1] Materials and Processing Report, Renee Ford, Ed., MIT Press, Cambridge, MA, February, 1987.

SYSTEMS APPROACH TO COSTS

It is often stated that the three biggest barriers to the increased use of advanced materials are cost, cost, and cost. In a narrow sense, this observation is correct. If advanced materials are considered on a dollar-per-pound basis as replacements for steel or aluminum in existing designs, they cannot compete. This has often been the perception of potential user industries, which tend to be oriented toward metals processing. However, per-pound costs and part-for-part replacement costs are rarely valid bases for comparison between conventional and advanced materials.

A more fruitful approach is to analyze the overall systems costs of a shift from conventional materials to advanced materials, including integrated design, fabrication, installation, and lifecycle costs.[2] On a systems cost basis, the advanced materials can compete economically in a broad range of applications. Moreover, the high per-pound cost is largely a result of the immaturity of the available fabrication technologies and the low production volumes. Large decreases in materials costs can be expected as the technologies mature. For instance, the cost of a pound of standard high-strength carbon fiber used to be $300 but is now less than $20, and new processes based on synthesis from petroleum pitch promise to reduce the cost even further.[3] If high-strength carbon fibers costing only $3 to $5 per pound were to become available, major new opportunities would open up for composites in automotive, construction, and corrosion-resistant applications.

Advanced ceramics and composites should really be considered structures rather than materials. Viewed in this light, the importance of a design process capable of producing highly integrated and multifunctional structures becomes clear. Polymer matrix composites (PMCs) provide a good example. In fact, the greatest potential economic advantage of using such materials, beyond their superior performance, is the reduction in the manufacturing cost achieved by reducing the number of parts and operations required in fabrication. For example, a typical automobile body has about 250 to 350 structural parts. Using an integrated composite design, this total could be reduced to between 2 and 10 parts, with major savings in tooling and manufacturing costs.[4]

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[2] "How Should Management Assess Today's Advanced Manufacturing Options," *Industry Week*, May 26, 1986, pp. 45-88.

[3] *Iron Age*, June 20. 1986, p. J6.

Fuel Costs

Fuel costs also represent an important factor that can affect the competitiveness of advanced ceramics and composites compared with conventional structural materials. The cost of the energy required to manufacture ceramic and composite components is only a negligible fraction of overall production costs. However, the high potential for energy savings when the component is in service is a major reason for using advanced ceramics and composites.[5]

Penetration of ceramics into such applications as heat exchangers, industrial furnaces, industrial cogeneration, fluidized bed combusters, and gas turbine engines depends on energy costs. Ceramic heat exchanger systems have potential for greater than 60 percent fuel savings.[6] Ceramics used in advanced turbines could result in 30 to 60 percent fuel savings.[7]

Weight reduction, through intensive use of PMCs in automobiles, may be translated into improved fuel economy and performance, and thereby lower vehicle operating cost. The trend toward fuel-efficient automobiles after the oil crisis of 1973-74 resulted in a substantial decrease in the average weight of an automobile, some 25 percent of it due to the introduction of lightweight materials such as high-strength steel, plastics, and aluminum.[8] Increases in fuel prices would encourage some further interest in advanced composites for automotive applications. (For further discussion of the impact of energy costs on use of composites in automobiles, see chs. 6 and 7.)

In aircraft, one of the major benefits of using PMCs is lower lifecycle costs derived from better fuel efficiency, lower maintenance costs and longer service life. This has already been demonstrated by the fact that there was a significant increase in the use of PMCs in aircraft when oil prices were greater than $30 per barrel.[9] It is also evident however, that lifecycle costs and capital, materials, and labor costs (notably the high labor costs of hand lay-up) are design trade-offs which determine the choice of materials. When oil prices drop as low as $12 per barrel (as they did in the fall of 1986), the relatively high cost of composite materials makes them unattractive to the aircraft manufacturer.[10]

There are predictions that low oil prices will continue through the year 2000, and that jet fuel prices will not even increase as quickly as crude oil prices.[11] This does not necessarily mean that gains made in use of composites in aircraft will be reversed. Rather, the persistent low energy costs are likely to reduce the incentives to increase the use of composites in structures now made of aluminum.

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[4] P. Beardmore et al., Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries—Case Study: Composite Automobile Structure," contractor report for OTA, March 1987.

[5] David W. Richerson, "Design, Processing, Development and Manufacturing Requirements of Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

[6] S.M. Johnson and D.J. Rowcliffe, SRI International Report to EPRI, "Ceramics for Electric Power-Generating Systems," January 1986.

[7] Richerson, op. cit., December 1985.

[8] Steven R. Izatt, "Impacts of New Structural Materials on Basic Metals Industries," contractor report for OTA, April 1987.

[9] A.S. Brown, "Pace of Structural Materials Slows for Commercial Transports," *Aerospace America*, American Institute of Aeronautics and Astronautics, June 1987, pp. 18-21, 28.

[10] Ibid.

[11] P.D. Holtberg, T.J. Woods, and A.B. Ashby, "Baseline Projection Data Book," Gas Research Institute, Washington, DC, 1986.

EDUCATION AND TRAINING

The expanding opportunities for advanced ceramics and composites will require more scientists and engineers with broad backgrounds in these fields. At present, only a few U.S. universities offer comprehensive curricula in ceramic or composite materials. There is also a shortage of properly trained faculty members to teach the courses. However, considerable progress is being made in the number of students graduating with degrees in advanced materials fields. In the

1984-85 academic year, a total of 77 M.S. degrees, and 34 Ph.D.s were awarded in ceramics in the United States. One year later the totals were 139 and 78, respectively. About 40 percent of the Ph.D.s were foreign students. No estimates were available on how many of the foreign students subsequently returned to their home countries.[12]

The job market for graduates with advanced degrees in ceramic or composite engineering is good, and can be expected to expand in the future. Stronger relationships between industry and university laboratories are now providing greater educational and job opportunities for students, and this trend is expected to continue.

There is a great need for continuing education and training opportunities in industry for designers and engineers who are unfamiliar with the new materials. In the field of PMCs, for instance, most of the design expertise is concentrated in the aerospace industry. Continuing education is especially important in relatively low-technology industries such as construction, which purchase, rather than produce, the materials they use. Some universities and professional societies are now offering seminars and short courses to fill this gap; such educational resources should be publicized and made more widely available.

Beyond the training of professionals, there is a need for the creation of awareness of advanced materials technologies among technical editors, managers, planners, corporate executives, technical media personnel and the general public. In recent years, there has been a marked increase in the number of newspaper and magazine articles about the remarkable properties of advanced ceramics and composites, as well as in the number of technical journals associated with these materials. The success of composite sports equipment, including skis and tennis rackets, shows that new materials can have a high-tech appeal to the public, even if they are relatively expensive.

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[12] Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," contractor report for OTA, Jan. 28, 1987.

MULTIDISCIPLINARY APPROACH

Commercialization of advanced materials requires a team effort. In producing a typical ceramic component, the team could consist of one or more professionals from each of several technical disciplines, as illustrated in table 5-2. Disciplines that overlap materials science and engineering are: solid state physics; chemistry; mechanical, electrical, and industrial engineering; civil and biomedical engineering; mathematics; and aerospace, automotive, and chemical engineering. Materials research lends itself naturally to collaborative institutional arrangements in which the rigid disciplinary boundaries between different fields are relaxed.

Similarly, intersector cooperation in materials research could speed the development of advanced materials. New mechanisms for collaborative work among university, industry, and government laboratory scientists and engineers are having a salutary effect on the pace of advanced materials development and utilization. (The role of government/university/industry collaborative R&D is explored in greater detail in ch. 10.)

Table 5-2.—Hypothetical Multidisciplinary Design Team for a Ceramic Component

Specialist	Contribution
Systems engineer	Defines performance
Designer	Develops structural concepts
Stress analyst	Determines stress for local environments and difficult shapes
Metallurgist	Correlates design with metallic properties and environments
Ceramist	Identifies proper composition, reactions, and behavior for design
Characterization analyst	Utilizes electron microscopy, X-ray, fracture analysis, etc. to characterize material
Ceramic manufacturer	Defines production feasibility

SOURCE: J.J. Mecholsky, "Engineering Research Needs of Advanced Ceramics and Ceramic Matrix Composites," contractor report for OTA, December 1985.

STANDARDS

There are many problems inherent in setting standards in rapidly moving technologies.[13] Standards development is a consensus process that can take years to complete, and it is likely to be all the slower in this case because of the complex and unfamiliar behavior of advanced ceramics and composites. As these technologies mature, though, such difficulties will generally become more tractable.

The extensive data requirements of integrated design can be simplified by material standards to reduce the volumes of data that are processed, and by data transfer standards to permit the efficient handling of data. Standards are essential for the generation of design data, and for reliability specifications for advanced materials sold domestically or abroad. Areas that could benefit from the formulation and application of standards include: quality control, product specifications, and, most importantly, materials testing.

The two keys to competitiveness in any area of manufacturing are quality assurance at low cost. Quality control standards applied at each stage of the manufacturing process help to ensure high product quality and low rejection rates. For instance, there is a need for standards applied to ceramic powders and green bodies (unsintered ceramic shapes) to minimize the flaws in the final sintered product. Product specification standards, largely determined by the requirements of the buyer, provide the buyer with assurance that the product will meet his needs.

As a way to accelerate the commercialization of advanced materials, some experts advocate choosing one or two materials in a given category and concentrating on producing uniform, high-quality components from these. In ceramics, for instance, silicon carbide, silicon nitride, and zirconia would be possible candidates, because they have already received a large amount of research funding over the years for heat engine applications. These materials have a broad range of potential uses, but designers cannot compare them or use them without a reliable database on standard compositions having specified properties. While there is a danger in prematurely narrowing the possibilities, these experts say, there is also a danger in not developing the materials already available. Opponents of this view argue that, since large commercial markets are still far in the future, there is no need to settle for present materials and processes. On the contrary, they say, the focus should be on new materials and processes which can "leapfrog" the present state-of-the-art. This classic dilemma is characteristic of any rapidly evolving technology.

Standard Test Methods

The need for standard test methods has long been identified as an important priority. For homogeneous materials such as metals, testing methods are fairly straightforward. In composites, however, the macroscopic mechanical behavior is a complex summation of the behavior of the microconstituents. Consequently, there has been great difficulty in achieving a consensus on what properties are actually being measured in a given test, let alone what test is most appropriate for a given property. Currently there are numerous test methods and private databases in use throughout the industry. This has resulted in considerable property variability in papers and reports. The variability problem is particularly severe for testing of toughness, bending, shear, and compression properties.

Standardized test methods would not only facilitate consistent reporting of materials properties in the research literature, but they could also drastically reduce the costs of the repetitive testing presently necessary to qualify new materials for use in various applications.[14] Due to liability concerns, a new material must be qualified by extensive testing for an individual application before a user company will incorporate it into a system.

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[13] J. David Roessner, "Technology Policy in the United States: Structures and Limitations," *Technovation*, vol. 5, 1987, p. 237, provides a brief case study of problems in setting standards in the early stages of development of numerically controlled machine tools.

[14] This is discussed for polymer matrix composites in ch. 11.

At present, each defense prime contractor company qualifies its material for each separate defense or aerospace application according to its own individual tests and procedures. Data on material properties are often developed under government contract (costing $100,000 to $10 million and taking up to 2 years), but companies are reluctant to share the results. Even when data are reported in the literature, often the type of test used and the statistical reliability of the results are not reported with the data. Although the lack of standards probably does not inhibit the expert designer of composite aerospace structures, the availability of standards could encourage the use of composites in industries such as construction, where designers have no familiarity with the materials.

U.S. Standardization Efforts

The American Society for the Testing of Materials (ASTM), provides the United States with an excellent and internationally respected mechanism for setting materials standards. ASTM has recently established an Advanced Ceramics Committee (C-28), which is now staffing subcommittees in the fields of properties, performance, design and evaluation, characterization, processing, and terminology. The ASTM Committee on High Modulus Fibers and Their Composites (D-30) and the Committee on Plastics (D-20) are the principal sources of standardized test methods for PMCs. Advanced materials trade associations such as the United States Advanced Ceramics Association (USACA) and the Suppliers of Advanced Composite Materials Association (SACMA) have also been working with ASTM and government agencies to develop standards.

On the users' side, the Aircraft Industries Association has initiated Composite Materials Characterization, Inc. (CMC), a consortium of aerospace companies involved in fabricating composites. CMC is conducting limited materials screening tests on composite materials for its members.[15]

Consistent with its growing interest in composites, the Department of Defense, with the Army as the lead service, has recently initiated a new program for standardization of composites technology (CMPS).[16] CMPS is attempting to promote the integration of diverse standards for composites by gathering standardized test methods (e.g., from ASTM) into Military Handbook 17 (MIL-17) and by developing separate test methods where necessary.[17] A Joint Army-Navy-NASA-Air Force (JANNAF) Composite Motor Case Subcommittee is developing standard test methods for filament wound composites used for rocket motor cases.[18]

As part of CMPS, the Army Materials Laboratory in Watertown, MA, has established coordination with a variety of organizations, including ASTM, the Composites Group of the Society of Manufacturing Engineers (CoGSME), the Society of Automotive Engineers (SAE), the Society for the Advancement of Material and Process Engineering (SAMPE), American Society for Metals (ASM) International, the Society of Plastics Engineers (SPE), and the Society of the Plastics Industry (SPI).

International Standardization Efforts

International organizations that are pursuing advanced materials standards include the Versailles Project on Advanced Materials and Standards (VAMAS), and the International Energy Agency (IEA). VAMAS is now formally independent, having begun as an outgrowth of the periodic summit meetings of the heads of government of Canada, France, the United Kingdom, West Germany, Italy, Japan, the United States, and the European Community. Subdivided into 13 technical working areas, VAMAS is attempting to improve the reproducibility of test results among laboratories by round robin testing procedures designed to identify the most important control variables. U.S. liaison with VAMAS is primarily through the National Bureau of Standards (NBS).

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[15] *Advanced Composites*, July/August 1987, p. 45.

[16] U.S. Department of Defense, Standardization Program Plan, Composites Technology Program Area (CMPS), Mar. 13, 1987.

[17] A draft of MIL 17 was being evaluated at this writing.

[18] U.S. Department of Defense, op. cit., footnote 16.

The IEA is developing standards for characterizing ceramic powders and materials. The principal participants are the United States, Sweden, and West Germany. U.S. liaison with the IEA is coordinated through the Department of Energy. Currently, U.S. participation in these international standards-related activities tends to be limited, with funds being set aside from other budgets.

AUTOMATION

The term automation is used here to encompass the wide range of new design and processing technologies for advanced materials. Automation of design and early development work involves standardized materials and processing databases; *computer-aided design* (CAD) systems; and computerized *mathematical modeling* of design and processing of the material. Automation of production processes can involve any combination of the following technologies: *computerized processing equipment* that can be used in a stand-alone fashion or in coordination with other technologies; *robotic*, instead of human, handling of material; *sensors* and process monitoring equipment; *statistical process control* for better part quality; *computer-aided manufacture* (CAM) and *"expert" systems* software for coordination of design and manufacture.

Computer-Aided Design Systems

CAD systems currently focus on three-dimensional graphics manipulation, and many of them also have the capability for stress analysis of a structure. CAD systems for mechanical drawings currently cannot recognize parts of a drawing as significant features; e.g., the collection of lines that a designer sees as a hole is seen by the CAD system as simply a collection of lines.[19] [20] A comprehensive CAD system that would facilitate the process of choosing suitable materials, reinforcement geometry, and method of fabrication is still far in the future. Such a system would require both materials databases on fiber and resin properties and processing databases that would permit modeling of the manufacturing steps necessary to fabricate the part. The principal advantage of such a system would be to define clearly the options and trade-offs associated with various production strategies, including processing costs.

Computerized Mathematical Modeling

To expand the capabilities of a CAD system, the designer would need accurate models of how the material and the part would behave in the operating environment. Computerized mathematical models will be necessary to describe the relationships among materials properties, material microstructures, environmental conditions, static and dynamic forces, manufacturing variables, and other aspects of design such as life prediction and repairability considerations. Mathematical models may also aid in decreasing the amount of stored data needed. It may also prove possible to develop, during the design of a given component, temporary mathematical models, specific to that component. This would facilitate quick redesign of the component during the design or prototype development phases.[21]

Computerized Processing Equipment

Computer control of all aspects of processing and manufacturing will be an important factor in increasing and maintaining the reliability and reproducibility of parts made of advanced materials. What is required initially is processing equipment similar to today's computer numerically controlled (CNC) machine tools for machining metal. Automated processing equipment is being designed in-house by some aerospace manufacturers and manufacturers of machine tools.

Currently, production equipment (computer controlled or otherwise), designed specifically for advanced materials is at a prototype stage. An example is automated tape-laying machinery for

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[19] Herb Brody, "CAD Meets CAM," *High Technology*, May 1987, pp. 12-18.

[20] More sophisticated CAD systems exist for drawing electronic circuits.

[21] Norman Kuchar, General Electric Co., personal communication, Apr. 15, 1987.

PMCs. The tape-laying machines now available are modified milling machines similar to those used for metalworking. There is a great deal of interest in developing new programmable automated tape-laying equipment, with computer-aided determination of the tape-laying path.[22]

Another promising technology for automating PMC production is the filament winding machine. Recent development work in flexible filament winding machines indicates that it may be possible to generate complex, noncylindrical parts.[23]

Other processes for producing composite parts that are good candidates for computerized processing are: fast pultrusion processes, impregnation of prepregs, and three-dimensional fabrics and preforms.

Ceramic processing techniques that could benefit from this sort of automation are shaping and densification methods, machining techniques, and particularly techniques for near-net-shape processing, such as hot isostatic pressing and casting techniques.

Microprocessors can monitor and control cycle times and temperatures for such processes as hot isostatic pressing for ceramics and fast-curing spray-up processes for PMCs. Equipment under computer control will eventually be used in part finishing operations and assembly as well as part forming.

Robotics and Materials Handling

Robots function as would a human hand and arm in manipulating parts and materials. Robots can also be used to hold and operate tools, such as welding equipment or drills. Processes such as hand lay-up of composites currently require a great deal of human handling of material, but it is not necessarily cost-effective to replace a human with a robot directly in advanced material production. Processes such as filament winding and resin transfer molding are more likely to replace hand lay-up cost-effectively for certain types of composites.[24] For this reason, applications for robots in advanced material production are likely to be limited to the carrying of nondestructive evaluation sensors (see below) and a small amount of part handling. Robots are currently used for assembly operations such as welding. It may be that robots will be used in composite joining operations, such as the application of adhesives.

Sensors and Process Monitoring Equipment

To monitor advanced materials processing online (during the process), sensors are needed. This information must be sent to the computer and analyzed, so that errors can be detected and any needed corrections can be made while the part is still being formed. This procedure permits near-instant correction of costly mistakes in processing. This is accomplished through the use of sensors and monitoring equipment that can detect abnormal conditions without interfering with normal processes. Sensors are used not only to detect major processing problems but also for the fine-tuning of quality control.

There are many types of sensors: laser and other visual sensors, vibration-sensing monitors that can operate in many frequency ranges, force and power monitors, acoustic and heat-sensing probes, electrical property probes (e.g., capacitance- or inductance-based) and a host of other types. There are also many types of sensors that can be used for part inspection once a part has been completed; these include such techniques as nondestructive evaluation (using acoustic and other vibrational methods, radiography, holography, thermal wave imaging, and magnetic resonance among other methods) and use of laser-based high-precision dimensional measuring machines.

Statistical Process Control

Quality control, in a general sense, means staying within predetermined tolerances or specifications when manufacturing a batch of parts. Each batch of parts has a statistical distribution of part

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[22] Roger Seifried, Cincinnati Milacron Co., personal communication, June 1, 1987.

[23] Dick McLane, Boeing Airplane Co., personal communication, Apr. 29, 1987.

[24] Timothy Gutowski, Massachusetts Institute of Technology, personal communication, Apr. 15, 1987.

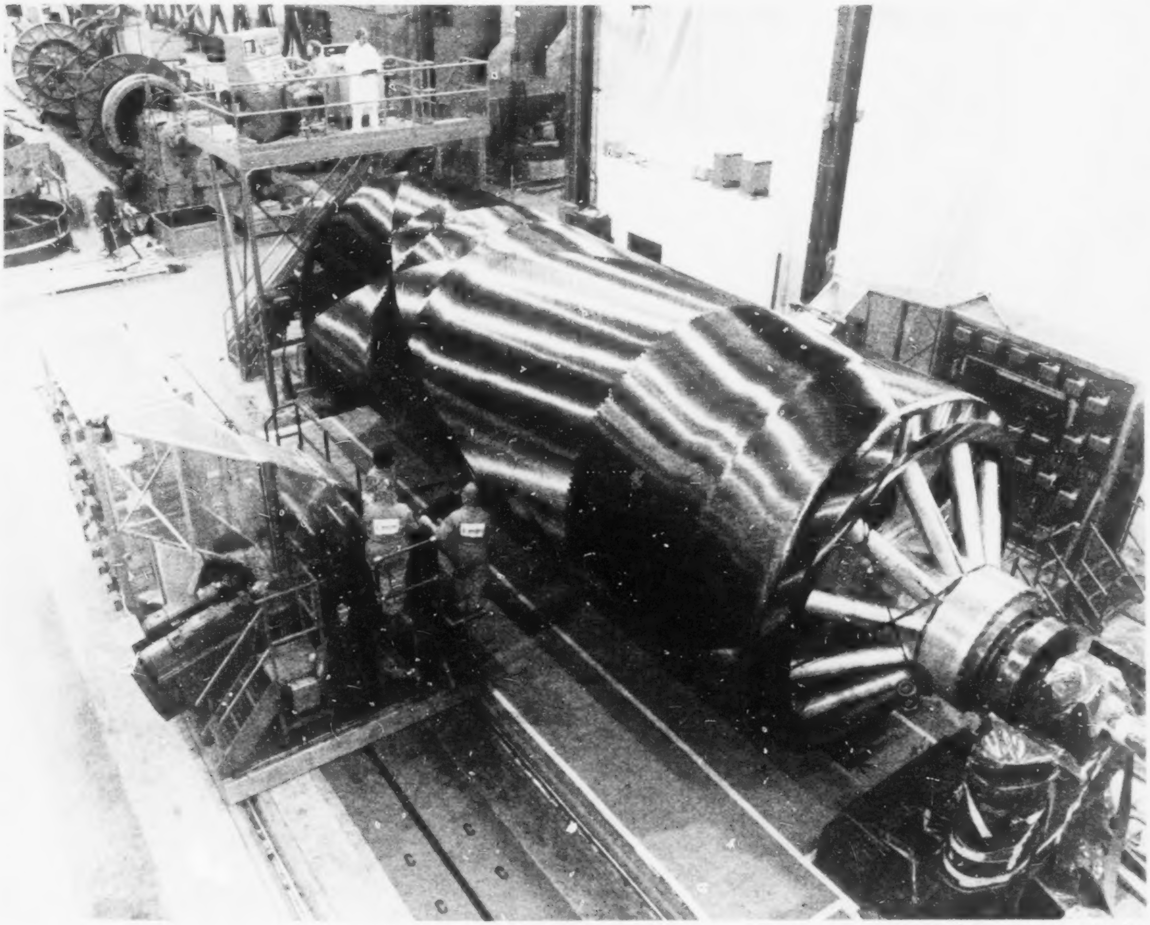

Photo credit: Hercules, Inc.

Filament winding of rocket motor casing for space shuttle.

qualities, all of which must fall within a certain tolerance range. Statistical process control encompasses quality-control practices that ensure that the statistical part quality distribution falls within the tolerance range, and that this distribution is *centered* within the tolerance range.[25] This procedure ensures not only that part quality of all the parts in the batch is acceptable, but also that the large majority of the parts in the batch are of the most desirable quality.

Statistical process control is mainly mathematical in nature and relies heavily on the sensor technologies described above for information inputs. To apply the information gained from statistical process control techniques most effectively, feedback into the manufacturing system must occur during the process of forming the batch. The information fed back into the process is used to make the minor processing corrections that can significantly increase the reliability of the process, enhance the overall quality of each batch, and reduce the rejection rates of the final parts.

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[25] Keith Beauregard, Perceptron Inc., "Use of Machine Vision To Stay Within Statistical Process Control Limits of Dimensions," Cutting Tool Materials and Applications Clinic, Detroit, MI: Society of Manufacturing Engineers, Mar. 11-13, 1986.

Computer-Aided Design and Manufacturing

CAD/CAM technology lies further in the future than most of the automation technologies described here. The CAD systems described above could help the designer choose a material and pick the least costly, most sensible process for manufacturing, as well as model the behavior of the part in service. A fully integrated CAD/CAM system would then send instructions to the correct set of machines to process the material. It would also need to include instructions for process variables, raw materials inventory, manufacture or supply of tooling, production time scheduling, and other shop-floor considerations.

Expert Systems

Expert systems technology, like the CAD/CAM technology, lies far in the future. An expert system is essentially a type of artificial intelligence and requires an extremely complex program that can make educated guesses when confronted with a lack of hard knowledge. Such a system is an assemblage of interactive software plus databases that offer all of the working knowledge gleaned by experts in a particular field. A designer inexperienced with composites or ceramics might be able to use the system to learn how to design with the unfamiliar material. The benefits of an expert system for materials design are clear. These materials could become more accessible with the advent of such an expert system, and all designers, whatever their level of experience, would have an enhanced base on which to draw.

CONSIDERATIONS FOR IMPLEMENTING AUTOMATION

Full automation implies an integration of all facets of design, development, materials inventory, production, quality assurance, product inventory, and marketing. Clearly such a degree of automation is far in the future for advanced materials and will only occur when the dollar volume of advanced materials products is high enough to warrant the significant capital investment needed for this type of production. Although this degree of technical complexity is not yet available, all of these technologies are individually of continuing interest to advanced materials manufacturers.

It is important to note that this type of complete automation need not occur at once. In fact, for reasons of capital cost alone, it is wise not to implement a high degree of automation quickly. Fortunately, some of these technologies can be verified and put in place well before others are available. It is necessary for each industry or company to decide what benefits of automation are most important and to choose to incorporate those forms of automation that could fill the needs of that company in a timely and cost-effective fashion.

Many industry experts feel that technologies such as advanced ceramics and composites are too new to warrant a large investment in automation. Automation is seen as an inflexible process requiring fixed, well-characterized processing techniques. In the view of these experts, it will be many years before enough experience has been gained with these materials to consider automation cost-effective. It will be useful to consider here what automation technologies offer for composites and ceramics manufacture and what challenges face the automation of advanced material production.

Automation offers three advantages: speed, reliability/reproducibility, and cost. However, these benefits cannot be realized simultaneously; trade-offs are required. A system that offers sophisticated controls and sensors for producing parts to tight specifications may not be a system that has enough speed (or low enough costs) to use in high-volume applications. The capital investment required may not be low enough to make advanced materials attractive enough to use even in high-volume applications. Another trade-off is between flexibility and speed/cost. Robots or materials processing equipment that can perform a wide range of tasks will not be as inexpensive and operationally quick as equipment dedicated to one particular task.

Currently, there are several major roadblocks to automation in the advanced materials field. One is the inability to link machine tools, controllers, and robots made by different manufacturers, or even by the same manufacturer at different points in time. This problem of interfacing nonstandard and dissimilar machines has been under consideration by a number of organizations, most notably the Automated Manufacturing Research Facility (AMRF)[26] at the National Bureau of Standards (NBS) and the Manufacturing Automation Protocol (MAP)[27] system developed by General Motors. Some advanced materials advocates have cited data transfer standards as some of the most important standards needed for increased use of advanced materials.

Another difficulty in automation is the wealth of information needed in electronic form which presents difficulties in data collection and increased probability of errors during data access. To illustrate the formidable problems facing the development of electronic databases of ceramic and composite properties, consider the state of metal machining databases. There are currently thousands of metals and metal alloys, and thousands of types of microstructure that can occur in each metal or alloy. Machining conditions can change with: microstructure of the metal; the type of machining process; the type, size and condition of tool; the depth, length, width, and speeds of cut; and the type and amount of lubricant. Each of these parameters must be selected for each operation that must be performed on a metal part.

In addition, unexpected machining behavior may occur depending on factors that cannot be known in advance, such as the rigidity, age, and brand of machine tool used. Thus, individual corrections must be made after the original parameters are chosen and tested.

There are similarly a large number of variables for the design of a metal part. At present, most of the country's design and production engineers working with metals use handbooks of incomplete tables to make best guesses as to design and process parameters. These data have been derived experimentally in an uncoordinated fashion over a period of decades. The situation for composites databases is even more complicated because of the larger number of component materials and materials interactions that must be taken into account.

Advanced Structural Materials Design

Most of the problems described above are present whether the material is metal, ceramic, or a composite. However automation is a much more problematic undertaking with advanced ceramics or composites than with metals. One major problem is the complexity of design.

At this stage, design databases, both for materials properties and the processes used in manufacturing parts, are still incomplete for available and familiar metals that have been in use for some decades. With newer materials this is even more of a problem because there is little material experience or history available from any source. Some experts believe that the use of mathematical modeling of manufacturing processes will eventually allow the designer to construct a part-specific database as a new part is being designed. This preliminary database could be updated as the design moved to the prototype and production phases and more knowledge of the material is gained.

One esoteric problem in automating design processes involves engineering knowledge of an intuitive or experiential nature. This human knowledge is difficult to translate into information that can be transferred or used electronically. Examples: The ability to tell the temperature of a molten metal by its color, or to ascertain the service life left to a cutting tool by the sound it makes during the cut. To translate this kind of know-how into electronic data, extremely accurate, sensitive, durable, and reliable sensors are required. This is particularly important considering the flaw sensitivity of such a material as a ceramic, because a large number of parts can be ruined for a slight margin of error in the sensor. These materials cannot be reworked, and high scrap rates are a major factor contributing to the high cost of ceramic parts.

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[26] "Automated Manufacturing Research Facility," National Bureau of Standards, December 1986.

[27] Catherine A. Behringer, "Steering a Course With MAP," *Manufacturing Engineering*, September 1986, pp. 49-53.

Advanced Structural Materials Production

Several problems are likely to hamper the development of automated techniques for production of advanced materials that do not arise in the production of parts made from metal. Although new structural materials offer the advantage of combining what would be several metal parts into a single structure, when an error occurs in production, cost-efficiency may be seriously threatened. Advanced materials cost more, the structure cannot be reworked, and the whole composite or ceramic structure is lost where only a single metal part might have been with a metal design. This is another reason why automated production of these advanced materials will require extremely reliable and accurate sensors.

Another problem is the large capital investment involved in automation. Full automation of design through production requires many new and expensive changes at once. Even though one of the main advantages of these new engineered materials is the integration of design and manufacturing, it will not be possible to develop all these technologies at once into a single, unified factory system.

As companies begin to automate, they will use different combinations of automation technologies, depending on the priorities of the user industry. Table 5-3 illustrates how the reasons for automating might differ among manufacturers. In the near term, automation based on the use of robotics to reduce labor costs may not be cost-effective if labor costs are a small part of overall cost, or if part volumes are low.[28] The automobile industry would desire to automate to save materials and manufacturing process costs.

In the aircraft industry, techniques such as automated tape laying to save the labor costs of hand lay-up could be important. Where long design times mean a significant cost, such as in aircraft design, automation is desirable in the form of mathematical modeling, expert systems for designers, and systems for prototype production, such as mold design software.[29] Since the reliability and reproducibility of ceramic parts are of primary importance, automated processing tech-

Table 5-3.—Reasons for Automating, and Appropriate Types of Automation

Reason	Types of automation	Industry example
Save labor costs:	Robotics New processing technologies (i.e., filament winding, tape laying)	Automotive paint spraying, joining
Speed up production:	New processing technologies: High-speed resin transfer molding, automated tape laying	Auto body
Increase part quality:	Process controls, sensor technologies	Ceramic auto engine parts Composite aircraft structures
Shorten design times:	Expert sytems CAD Mathematical modeling Databases	Composite aircraft structures

NOTE: Different manufacturing challenges require different types of automation solutions.

SOURCE: Office of Technology Assessment, 1988.

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[28] S. Krolewski and T. Gutowski, "Effect of the Automation of Advanced Composite Fabrication Process on Part Cost," *SAMPE Quarterly*, October 1986.

[29] Norman Kuchar, General Electric Co., personal communication, Apr. 15, 1987.

niques and sensor technology would be used to automate the manufacture of ceramics. The plastics industry is turning to robots for several reasons, among them the ability to integrate plastic part manufacturing with "downstream" assembly operations, and flexibility to meet changing production requirements.[30]

The one form of automation nearly all industries require immediately involves better materials processing technologies possessing some degree of automation. This means an increase in the quality of sensors and a higher level of sophistication in equipment for forming advanced materials. As we have seen and will see again in the following chapters, processes such as automated tape laying of PMCs and near-net-shape processes for ceramics will need precision forming and monitoring equipment to begin to offer the needed reliability and cost savings.

Automation techniques that foster integrated design through promoting close cooperation between designer and manufacturing engineer should be of highest priority. These would include extensive design databases, automated processing equipment and sensors for process information feedback.

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[30] Robert V. Wilder, "Processors Take a Second, Harder Look at Robots," *Modern Plastics*, August 1987, p. 48.

Chapter 6

Impacts of Materials Substitution on the Basic Metals Industries

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Chapter 6

Impacts of Materials Substitution on the Basic Metals Industries

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FINDINGS

The U.S. steel and aluminum industries are currently undergoing a substantial restructuring process caused by large increases in world supply and decreases in per capita demand. Overall, materials substitution has been only a minor factor affecting the demand for these metals in the past decade. However, the importance of substitution by alternative materials is likely to be significantly greater in the next 10 to 20 years.

The materials likely to have the greatest impact on the aluminum and steel industries are unreinforced plastics, polymer matrix composites (PMCs), metal matrix composites (MMCs), and high-strength concrete. Ceramics and ceramic matrix composites (CMCs) are not expected to have a significant impact on steel or aluminum use in the next 20 years.

The threat of substitution has stimulated improvements in metals technology, e.g., high-strength, low-alloy (HSLA) steels, aluminum-lithium alloys (Al-Li), and rapidly solidified metal alloys. This makes the pace of substitution difficult to predict.

An analysis of the end uses of these metals indicates that substitution is likely to be most important in four markets: aircraft, automobiles, construction, and containers. However, OTA finds that by far the greatest volume of metals will be displaced by relatively low-performance materials, such as unreinforced plastics, sheet-molding compounds, and high-strength concrete, rather than by so-called advanced materials.

As new materials are increasingly adopted, a variety of secondary industries, such as adhesives, coatings, and weaving industries can be expected to grow. The recyclability of the new materials could become a major factor affecting their use.

INTRODUCTION

With the development of new materials such as structural plastics and composites, engineers now have many more options available for designing products. These new materials can offer performance advantages over such traditional materials as aluminum, steel, and concrete. How will these new materials affect the traditional manufacturing industries? What new industries will develop to support the use of these materials? The answers to these questions are important to an understanding of the factors that will influence the evolution of U.S. manufacturing industries in the 1990s and beyond.

This chapter outlines the effects of materials substitution on the U.S. aluminum and steel industries.[1] An analysis of the major markets for these two metals suggests that the most significant possibilities for substitution will be in aircraft, automobiles, construction, and containers. In the following section, materials substitution is considered in the context of the many factors affecting supply and demand within the basic metals industries.

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[1] This chapter draws heavily on "Impacts of New Structural Materials on Basic Metals Industries," by Steven R. Izatt, a contractor report prepared for the Office of Technology Assessment, April 1987.

HISTORICAL SUPPLY AND DEMAND FACTORS FOR STEEL AND ALUMINUM

Supply

The supply of steel and aluminum worldwide has grown substantially in recent years. Major factors that have affected the supply of steel and aluminum in the United States are: the present U.S. overcapacity for steel and aluminum; the worldwide overcapacity for steel and aluminum; government ownership of foreign production facilities; volatile and depressed prices for steel and aluminum; imports of steel and aluminum, the growth of steel mini-mills in the United States; restructuring of the steel and aluminum industries; domestic scrap recovery of aluminum; and a shift to fabricated shapes in aluminum.

- *Overcapacity:* The main factor affecting the supply of steel and aluminum in the United States is the current domestic and worldwide overcapacity.
- *Foreign government ownership:* Abroad, many foreign governments own the national production of steel and aluminum. These governments thereby control commodity price, and this can lead to overproduction.
- *Steel and aluminum prices:* Prices are depressed for these commodities; often they are highly variable. This can be as damaging as continuous low prices, since fluctuating prices prevent long-term planning.
- *Imports:* Large volumes of foreign steel and aluminum are imported that are of good quality and of lower cost than can be found in the United States.
- *Mini-mills:* These smaller, more efficient steel mills are servicing some of the markets previously held by the larger integrated steel mills. This is very significant in product lines such as bar, rod, and wire, in which increased supply from mini-mills has caused overcapacity in the integrated steel mills.
- *Restructuring:* Both the aluminum and steel industries have been undergoing restructuring; for instance, the U.S. steel industry is evolving with the growth of mini-mills. Within individual steel and aluminum companies, restructuring is also taking place; for instance, the large U.S. aluminum producers are diversifying into other materials, particularly advanced materials, for their future business. This factor tends to reduce U.S. primary overcapacity.
- *Scrap recovery:* Recycling of aluminum has played a large part in its competitiveness. However, large amounts of recovered aluminum scrap also displace primary aluminum in several applications.
- *Shift to fabrication:* There has been a shift to supplying fabricated shapes rather than producing large units of steel (e.g., billets) to be shaped by the purchaser. This has little effect on total supply, but tends to favor industry restructuring toward mini-mills and away from integrated steel manufacturers.

Demand

The per capita demand for steel and aluminum has been continuously decreasing in the United States since its peak in the early 1970s.[2] The factors that have tended to decrease demand are: shifting consumption patterns, market saturation, more efficient use of materials, and materials substitution.

- *Consumer preferences:* Over the past 10 years, there has been a shift in consumer spending away from durable goods to services (table 6-1). This switch in spending preference is reflected in the decrease in the manufacturing sector's contribution to the national income since the late 1960s (down to 22 percent in 1983 from 30 percent in 1965[3]), and thus the decrease in per capita consumption of steel and aluminum.
- *Market saturation:* Analysts have observed that as a country matures past the rapid growth phase of its industrial development, the majority of the primary industrial infrastructure has been built. This results in a de-

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[2] Bureau of Economic Analysis, U.S. Department of Commerce, *World Almanac and Book of Facts, 1985*, p. 152.

[3] Ibid.

Table 6-1.—U.S. Personal Consumption Expenditures for 1978 and 1983 (billions of dollars)

	1978		1983	
	Expenditures	% of total	Expenditures	% of total
Durable goods:				
Motor vehicles & parts	$ 95.7	7.1	$ 129.3	6.0
Other	104.5	7.8	150.5	7.0
Total durable goods	200.2	14.9	279.8	13.0
Nondurable goods	528.2	39.2	801.7	37.2
Services	618.0	45.9	1,074.4	49.8
Total personal consumption expenditures	$1,346.4	100.0	$2,155.9	100.0

Between 1978 and 1983, personal consumption of services increased by nearly 4 percent, while consumption of durable and nondurable goods decreased by about 2 percent.

SOURCE: U.S. Department of Commerce, Bureau of Economic Analysis, *The World Almanac and Book of Facts*, 1985, p. 165.

crease in the ratio of materials consumption to per capita gross national product (GNP). In the United States, this ratio peaked for steel around 1950 and for aluminum in the mid-1970s, and is now declining.[4]

- *Efficient use of materials:* The use of a material becomes more efficient when a higher performance per pound of material is achieved. Producers have devoted significant R&D resources to develop steel and aluminum products and process technologies that require less steel or aluminum to satisfy a particular market need.
- *Materials substitution:* When a new material can offer a cost or performance advantage over the current material in an established application, the new material will begin to displace the old in that application. For instance, aluminum showed rapid growth in the post World War II era as it replaced such traditional materials as wood in construction, copper in high voltage transmission lines, and steel in beverage cans.

Interrelationships of Factors Affecting Supply and Demand

Domestic raw steel overcapacity is significantly increased by several factors that are outside of the control of the steel industry and act to increase supply. For instance, the factor of foreign government ownership of steel mills encourages foreign overproduction by mills not acting in response to market forces.

The problem of domestic overcapacity is also affected by worldwide overcapacity (this provides an increased incentive for importers to import to the United States). Industry restructuring (i.e., growth of mini-mills, plant closings and bankruptcy filings, joint venture and acquisition activity in new materials) has occurred as a response to domestic and worldwide overcapacity.

Materials substitution and efficient use of materials are strongly interrelated factors. The threat of materials substitution has encouraged producers to apply new technologies aimed at reducing the amount of material (and hence lowering the cost) required to meet consumer needs. In the steel industry, this interrelationship is seen in the case of HSLA steel and coated steels that have been developed in response to the threat by lightweight materials such as unreinforced plastics, PMCs, and aluminum.

Materials substitution significantly affects the trend toward more efficient use of aluminum. For instance, the increasing use of PMCs in aircraft applications has motivated the aluminum industry to provide lighter weight aluminum alloys and MMCs. To develop these advanced materials, the aluminum industry has undergone some restructuring in the form of joint ventures and acquisitions.

THE RELATIVE IMPORTANCE OF THE END USES OF STEEL AND ALUMINUM

To understand the impacts of substitution on the steel and aluminum industries, it is necessary to know the major markets for these materials. Tables 6-2 and 6-3 present industries classified in the most recent (1977) complete U.S. input-output tables, ranked in the order of highest use

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[4] E.D. Larson, M.H. Ross, and R.H. Williams, "Beyond the Era of Materials," *Scientific American*, 254(6):37, June 1986.

Table 6-2.—Industries Using the Largest Amount of Steel, 1977[a] (in millions of dollars at producers' prices)

Industry classification[b]	Use of steel	Percent	Potential for substituting alternative materials
1. Motor vehicles and equipment	9,471	15	High
2. Heating, plumbing, and fabricated structural metal products	5,700	9	Medium
3. Screw machine products and stampings	5,318	8	Low
4. New construction	4,567	7	Medium
5. Other fabricated metal products	3,791	6	Medium
6. Construction and mining machinery	2,880	5	Low
7. Metal containers	2,556	4	High
8. General industrial machinery and equipment	2,036	3	Low
9. Other transportation equipment	1,993	3	Low
10. Farm and garden machinery	1,432	2	Low
Total	39,744	62%[c]	

[a] Includes all categories listed under the Primary Iron and Steel Manufacturing Classification in the 1977 Input-Output Table: blast furnaces and steel mills, electrometallurgical products, steel wire and related products, cold finishing of steel shapes, steel pipes and tubes, iron and steel foundries, iron and steel forgings, metal heat treating, and primary metal products, not elsewhere classified.

[b] Includes all categories listed under these Industry Classifications.

[c] There are 85 industry classifications in the Input-Output tables. The remaining 38 percent of the total U.S. steel output is consumed by the 75 industries not listed here.

SOURCE: U.S. Department of Commerce, Bureau of Economic Analysis, *The Detailed Input-Output Structure of the U.S. Economy, 1977, Volume 1: The Use and Make of Commodities by Industries, 1977*, Washington, DC, 1984, pp. V-227.

Table 6-3.—Industries Using the Largest Amount of Aluminum, 1977[a] (in millions of dollars at producers' prices)

Industry classification[b]	Use of aluminum	Percent	Potential for substituting alternative materials
1. Heating, plumbing, and fabricated structural metal products	1,950	11	Medium
2. Motor vehicles and equipment	1,276	7	Medium
3. Metal containers	1,166	7	High
4. Other fabricated metal products	675	4	Medium
5. Aircraft and parts	488	3	High
6. Screw machine parts and stampings	465	3	Low
7. Service industry machines	447	3	Low
8. Electric industrial equipment and apparatus	338	2	Low
9. Other transportation equipment	291	2	Medium
10. Engines and turbines	289	2	Medium
Total	7,385	44%[c]	

[a] Includes the following categories under the Primary Nonferrous Metals Manufacturing Classification in the 1977 Input-Output Table: primary aluminum, aluminum rolling and drawing, and aluminum castings.

[b] Includes all categories listed under these Industry Classifications.

[c] There are 85 industry classifications in the Input-Output tables. The remaining 56 percent of the total U.S. aluminum output is consumed by the 75 industries not listed here.

SOURCE: U.S. Department of Commerce, Bureau of Economic Analysis, *The Detailed Input-Output Structure of the U.S. Economy, 1977, Volume 1: The Use and Make of Commodities by Industries, 1977*, Washington, DC, 1984, pp. V-227.

of steel and aluminum to lowest. Each of these industries has been further evaluated as to the possibility for alternative materials substituting for steel or aluminum. The industries that were both major consumers of steel or aluminum and that held a high potential for substitution were evaluated.

Table 6-2 shows that of the top 10 industries that use steel, 5 are judged to have a high or medium potential for substituting alternative materials.[5] The two industries of high potential are motor vehicles and equipment, and metal containers, both of which are covered in this assessment.

Of the three largest steel-consuming industries with a medium potential of substitution, construction is the only one covered in this chapter. The other two, screw machine products, stampings, and other fabricated metal products, are not analyzed here because these sectors cover such a diversity of types of products, each of limited dollar value on its own, that it is difficult to conduct a reliable, in-depth analysis.

Table 6-3 shows that of the top 10 industries that use aluminum, seven have a high or medium potential for substituting alternative materials.[6] Three of these seven, which are treated in this chapter, are aircraft and parts, motor vehicles and equipment, and metal containers. In the four industries of medium possibility not analyzed here (heating, plumbing, and fabricated structural metal products; other fabricated metal products; other transportation equipment; and engines and turbines) the great diversity of products again precludes a reliable analysis.

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[5] Izatt, op. cit., footnote 1, 1987.

Thus, the four end uses judged to be of greatest potential for substitution of new materials for traditional metals are: aircraft, motor vehicles, construction, and containers. In the category of motor vehicles, the analysis is entirely of the automobile industry. The analysis of the market for containers includes not only beverage containers but food packaging as well.

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[6] Ibid.

POTENTIAL FOR SUBSTITUTION IN THE AIRCRAFT INDUSTRY

About 3 percent of the total aluminum output and one percent of the total steel output (by dollar value) of the United States is consumed by the aircraft industry. Even though the aircraft industry is a minor market for pounds of aluminum shipped (approximately 5 percent of the transportation segment), it is an important one in terms of the value of the aluminum shipped, as well as in terms of the U.S. balance of trade. The aircraft market is performance-sensitive and is therefore willing to pay a premium for materials that increase performance. This market acts as a development market for advanced materials that have a high initial cost.

Currently, aluminum accounts for 80 percent of the structural weight of commercial aircraft.[7] In military aircraft, the percentage has varied from 65 percent in the 1960s (F-4) to 50 percent in the 1970s (F-15) and to 55 percent in the 1980s (AV-8B).[8]

Although PMCs, and less developed materials such as Al-Li alloys, MMCs, and rapidly solidified aluminum alloys, are all possible future contenders for aircraft, it may be some time before they actually displace traditional aircraft materials. The planning cycles of aircraft have a significant effect on materials substitution. A new material must be fully developed and qualified in time to be considered for use in the next generation of aircraft. Missing this cyclic "window" means that the material cannot be considered for use until a new generation of aircraft is developed. Each of the materials that are candidate substitutes for aluminum is at a different point in development.

Table 6-4 describes the possible use of advanced structural materials in aircraft applications. PMCs and MMCs have been or could be used in many Navy, Army, Air Force, National Aeronautics and Space Administration (NASA) or civilian commercial helicopters, aircraft, and space structures. To date, the motivation for this substitution has mainly been the opportunity to achieve weight savings. As the properties of these materials improve, their level of performance, and hence substitution, should also increase. More important, as more experience is gained with these materials, their associated costs could decrease, providing the major motivation for their use, especially in commercial aircraft.

Reducing aircraft weight increases fuel efficiency, which results in lower life-cycle costs. Significant reductions in weight and increases in strength are desired to meet fuel efficiency needs. Industry experts have projected that substantial weight savings could be achieved along with property improvements; for instance, a 30-percent weight savings could be obtained with a 200-percent increase in fatigue strength by using PMCs, and a 20-percent weight savings could accrue with an 80-percent improvement in stiffness using MMCs (see figure 6-1).

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[7] Standard and Poor's Industry Surveys, Metals-Nonferrous, Basic Analysis, July 10, 1986, pp. M76-M77.

[8] B.A. Wilcox, "Influence of Advanced Materials on the Domestic Minerals Industry," *Materials and Society*, 10(2):209, 1986.

Table 6-4.—Current and Proposed Use of Advanced Materials in Aerospace Structures

System	Structure	Material
Aircraft:		
Boeing 747	30% of exposed surface area, 1% of structural weight, secondary structures	fiberglass/epoxy
Boeing 767	rudders, elevators, spoilers, ailerons ducting, stowage bins, partitions, lavatories, escape system parts, leading- and tailing-edge panels, cowl components, landing gear doors, fairings	graphite/epoxy Kevlar/epoxy graphite-Kevlar/epoxy hybrid
F-15	secondary structure, empennage parts	graphite, boron/epoxy
F-18	10% by weight of total structure; primary structure, wing applications, sandwich panel skins	graphite/epoxy
Beech Starship I	90% of aircraft; primary and secondary structures	graphite/epoxy
ATF	40% of total structure; fuselage substructure, inlet structure, integral tankage, bulkheads, fins	graphite/polyimide or graphite/bismaleimide or silicon carbide/aluminum
Avtek 400	all primary and secondary structures	Kevlar/epoxy
Helicopters:		
AH-64 Apache	secondary structures, primary structures, i.e., fuselage, rotor blades	Kevlar/epoxy
AV-8BV/STOL	26% of total weight; forward fuselage horizontal stabilizer, elevators, rudder, overwing fairings, wing box skins and substructure, ailerons, flaps	graphite/epoxy
Boeing Vertol 234	center section of aft rotor assembly	graphite-fiberglass/epoxy hybrid
LHX, JVX	airframes (results in acquisition and operational cost savings, weight savings, increased damage tolerance, etc.)	graphite/epoxy, Kevlar/epoxy, fiberglass/epoxy, fiberglass/polyimide
Space shuttle	fuselage, frame support struts, payload bay doors, purging ducts system, filament wound pressure vessels, nose cap, wing leading edges, structural parts (increasing allowable temperature)	graphite-fiberglass/epoxy hybrid, graphite/epoxy, Kevlar/epoxy, carbon/carbon, graphite/polyimide

SOURCE: Steven R. Izatt, "Impacts of New Structural Materials on Basic Metals Industries," a contractor report prepared for the Office of Technology Assessment, April 1987.

A note of caution is appropriate here on the strong influence of fuel prices: If fuel prices do not increase during the next 10 years, PMCs could look less attractive compared to aluminum. Aircraft designers currently estimate that a pound of weight saved is worth $100 over the life of the aircraft. Fuel prices as of August 1986 were about 55 cents per gallon. It has been estimated that it would take at least a factor of 2 increase in these fuel prices to make PMCs look attractive to aircraft buyers.[9]

The important cost factors in considering advanced composites substitution for aluminum are life-cycle costs, as noted above, and production costs. The major improvement in future costs should come from improved fabrication methods. The contribution of the base material costs to overall structure costs is relatively small. For instance, lower stiffness (30 Msi) PAN-based graphite fibers generally sell for approximately $20 per pound. Prepreg tape made from these fibers and infiltrated with a resin system typically sells for approximately $40 per pound. The final cost of the finished aircraft structure can be in the range of $100 to $400 per pound.[10]

Another important cost consideration in comparing PMCs with metals is the significantly reduced number of parts made possible by using PMCs. For instance, in the Bell Helicopter Textron, Inc./Boeing Vertol prototype PMC helicopter body, the V-22 Osprey, there is a reduction in the number of airframe parts from 11,000 (aluminum) to 1,530 (PMC). The number of fasteners is reduced from 86,000 to 7,000. The weight reduction is from 4,687 lbs to 3,281 lbs.[11]

Figure 6-2 shows the potential savings in aircraft structural weight forecast for the next quarter-century. PMCs have the potential to give the largest weight reduction (30 to 40 percent) using advanced fibers with modified epoxies and ther-

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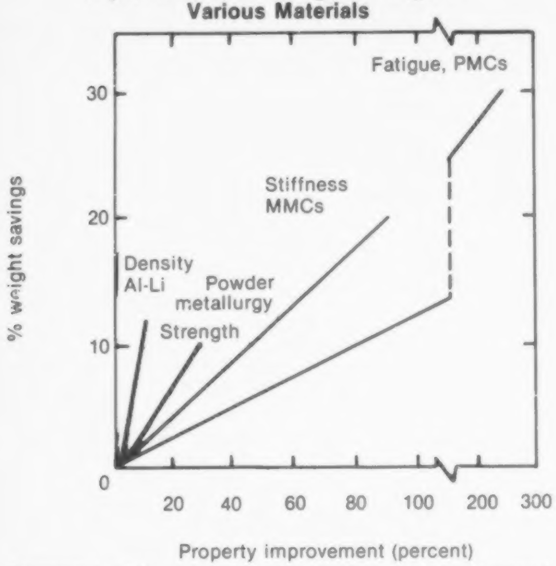
[9] Bob Hammer, Boeing Aircraft Co., personal communication, September 1987.

[10] D.R. Tenney and H.B. Dexter, "Advances in Composites Technology," *Materials and Society*, 9(2):188, 1985.

[11] P. N. Lagasse, "The Role of Reinforcing Fibers in Composites," *Rubber World*, May 1985, pp. 27-28.

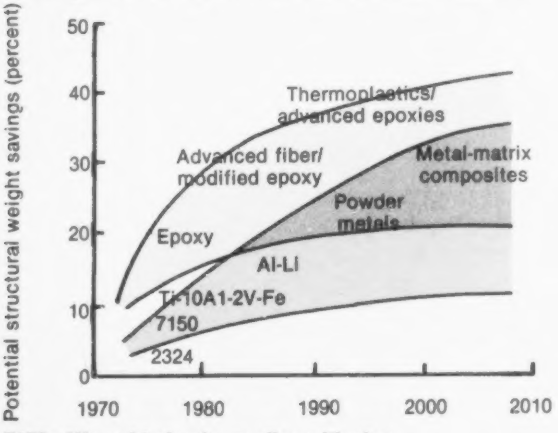
Figure 6-1.—Relationship Between Property Improvement and Weight Savings for Various Materials



Compared with conventional materials, using advanced materials offers improvements in mechanical properties as well as weight savings.

SOURCE: P.R. Bridenbaugh, W.S. Cebulak, F.R. Billman, and G.H. Hildeman, "Particulate Metallurgy in Rapid Solidification," *Light Metal Age*, October 1985, p. 18.

Figure 6-2.—Projected Savings in Aircraft Structural Weight Based on Selected Advanced Materials



7150—Wrought aluminum alloy with zinc.
2324—Wrought aluminum alloy with copper.

Advanced PMCs offer the greatest weight savings.

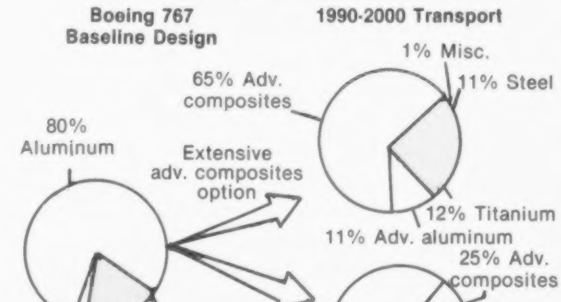
SOURCE: D.R. Tenney and H.B. Dexter, "Advances in Composites Technology," *Materials and Society* 9(2):186, 1985.

moplastic matrices. Al-Li and powder metallurgy (P/M) alloys are expected to be introduced over the next 5 to 10 years and offer a 10- to 15-percent weight savings.

The open question is whether aluminum (and its new alloys and composites) or PMCs, will be the material of choice in the next generation of commercial transport aircraft. Figure 6-3 shows two possible options (extensive use of new aluminum technologies or extensive use of PMCs) for a hypothetical commercial transport built in the 1990s. Due to recent improvements in resins, fibers, and processing technology for PMCs, and to higher-than-projected costs for aluminum alloys, the extensive PMC scenario currently looks very promising. However, the actual outcome is likely to lie in between these two scenarios.

The use of Al-Li alloys or rapidly solidified technologies would cause the total amount of aluminum used in aircraft applications to decline, since they are stronger per unit weight and/or less dense than traditional aluminum alloys. Whichever scenario (i.e., extensive use of PMCs or extensive use of new aluminum technologies as described in figure 6-3) occurs, the use of traditional alumi-

Figure 6-3.—Breakdown of Structural Materials Use in Two Alternative Designs of Commercial Transport Aircraft



In the option featuring extensive use of advanced aluminum, the proportion of aluminum drops by 26 percent due to improved structural efficiency. In the option featuring extensive use of advanced composites, the proportion of aluminum drops by 69 percent. Steel use remains virtually unchanged.

SOURCE: D.R. Tenney and H.B. Dexter, "Advances in Composites Technology," *Materials and Society* 9(2):194, 1985.

num could decrease by between 26 and 69 percent. Since aircraft and aircraft parts account for slightly less than 3 percent of total aluminum output in the United States (table 6-3), this decrease in aircraft use of aluminum could mean a 1 to 2 percent decrease in the dollar value of total U.S. aluminum use by the year 2000. Note that steel use remains roughly constant in either scenario.

POTENTIAL FOR SUBSTITUTION IN THE AUTOMOBILE INDUSTRY

In evaluating substitution in the automobile industry, it is very important to understand that the automotive market is a commodity market that is extremely cost-sensitive, compared to the high performance-oriented aircraft market. Thus, it is more difficult for new, high-performance (high-cost) materials to penetrate the automotive market, unless a significant cost savings can be realized.

During the past 20 years, three trends have had major effects on the materials content of automobiles in the United States. From 1967 to 1976, government standards encouraged automakers to add structural weight to make autos safer. In 1975 the passage of the Energy Policy and Conservation Act (Public Law 94-163) required yearly increases in the average fuel efficiency of each manufacturer's fleet of vehicles. This trend toward fuel-efficient cars resulted in a substantial decrease in the average weight of an automobile. The majority of this decrease can be attributed to downsizing and most of the remainder to use of high-strength steels, and to a lesser extent, unreinforced plastics and aluminum as substitutes for mild steel and iron.[12]

The most recent trend affecting the U.S. automobile industry has been the increase in international and domestic competition that has developed since about 1983. The industry has become increasingly cost- and quality-conscious as U.S. consumers have turned increasingly to imported vehicles. To compete in the low-growth automotive market, one of the strategies that automakers have used to keep market share is to appeal to a broad range of consumers in different market niches. For this reason, the number of major automotive nameplates is projected to increase from 68 in 1984 to 77 in 1989.[13] This market segmentation could mean that an increasing number of models will be made in smaller production volumes and model design could change more frequently.

The current trend toward market segmentation (more automotive models) could increase the likelihood of substitution, since sheet molding compound (SMC) fabrication is competitive with that of steel in low production volumes. The SMC composite-skinned Fiero, for instance, is assembled at the rate of only 100,000 cars per year while the annual production rate for the steel-bodied J-body cars (Cavalier, 2000 Sunbird, Firenza, Skyhawk, Cimarron) is 600,000. Most automobiles, because of the cost/benefit advantages for large production runs, still have steel body panels.

Major materials used in automobiles are mild steel, cast iron, HSLA steel, aluminum, unreinforced plastics, and so-called lower technology PMCs. These latter two are now just beginning to have a presence in the automotive market. The ability to mold unreinforced plastics, and reinforced plastics such as sheet molding compound, into aerodynamic shapes more easily than steel makes them strong contenders for increased substitution. Stimulated by this threat, new types of steel products—HSLA and coated steels—have become available, providing the potential for continued dominance of steel in automotive applications. The trend toward the increased use of precoated steels has also reduced the potential substitution of current unreinforced plastics for steel sheets.

Table 6-5 lists examples of where lighter weight materials such as unreinforced plastics, fiberglass and graphite-reinforced composites, aluminum, and HSLA steel are substituting for iron and steel in automobiles. These programs are a mixture of approved projects and projects that have been proposed. Most are secondary-structural or nonstructural applications such as fenders, door parts,

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[12] Izatt, op. cit., footnote 1, 1987.

[13] L. Leonard, "Automotive Materials War Heats Up," *Materials Engineering*, October 1985, p. 29.

Table 6-5.—Current and Proposed Use of Advanced Materials in Automobiles

Material/current use

Plastics:
- *Ford Merkur XR4Ti:* rear double spoiler (injection molded polycarbonate/acrylonitrile-butadiene-styren (PC/ABS)), instrument panel and glove compartment, door handles, radiator grille, light frames, rear package tray and center console[a]
- *Chrysler T-Vans (commercial version):* plastic back butterfly doors[b]
- *Ford Aerostar van (commercial version):* plastic back butterfly doors[b]
- *GM Fiero:* roof, decklid (SMC); fascias, fenders and doors (reaction-injection-molded urethane)[d]
- *Ford Aerostar van:* fuel tank, lamps, front and rear bumpers[i]

Composites:

—Fiberglass
- *Chevrolet Corvette:* body and transverse rear spring[c]
- *GM Eank cars:* leaf springs[e]
- *Ford Aerostar:* hood, rear liftgate[i]
- *Chrysler Dakota pickup:* leaf springs[b]

—Fiberglass/graphite
- *Ford Econoline van:* rear wheel drive shaft[c]

Aluminum:
- *Chevrolet Corvette:* driveshaft[h]
- *Ford Aerostar van:* driveshaft, one-piece wheels, rear axle carrier, oil pan, and enginemount brackets[i]
- *Ford Ranger pickup:* one-piece aluminum wheel[i]
- *Chrysler 2.5 L balance-shaft engines:* carriers for the balance shafts[k]
- *Chevrolet Corvette:* cylinder heads on 5.7 L V-8[i]
- *Dodge Dakota pickup:* intake manifold on 3.9 L V-6 engine
- *Lincoln Town Car:* inner and outer hood panels and hinge reinforcements[n]

Stainless steel:
- *Oldsmobile Toronado:* exhaust system from manifold to tailpipe[i]
- *Cadillac:* exhaust manifolds[i]
- *Ford Taurus/Sable:* exhaust pipes and supports[i]

High-strength steel:
- *Current or potential use:* 35-45 ksi—outer and inner body components such as door, hood, fender, deck, quarter, floor, pan, and dash panel; 50-60 ksi—rocker panel (side sill), front and rear rails, wheel, frame, control arm, bracket, bumper and reinforcement, seat track, and cross member; 70-80 ksi—door beam, bumper reinforcement, and bracket[j]

Material/proposed use

Plastics:
- *Buick LaSabre (1987):* front fenders[b]
- *Chrysler's P-body cars (1987):* bumper fascias[b]
- *Buick Reatta (1987):* front fenders[b]
- *Chrysler's imported Q-coupes (1987):* bumper fascias[b]
- *Ford Ranger pickup (1988):* plastic leaf springs[b]
- *Ford Tempo and Topaz (1988):* all plastic bumpers[b]

Plastics and composites:
- *GM composite bodied cars (GM80 Program):* Camaro and Firebird replacement cars (1991 was target date, but has been cancelled)[b]
- *Pontiac Fiero:* space frame[e]
- *Chrysler Genesis Program (1990s):* composite chassis[g]
- *Ford Alpha Program (1990s):* composite chassis[g]
- *GM-100 Program (1990s):* composite chassis[g]

Aluminum:
- *Ford F-trucks and Econoline van (1987):* aluminum drive shafts[h]
- *GM 3200 series V-6 engine (1989 Camaro and Firebird):* cylinder block, head, two inlet manifolds, oil pan, water pump, and pistons[i]
- *Audi (date unspecified):* entire body—formed jointly with Alcoa[l]
- *Chrysler Voyager, Caravan, and Daytona (1987):* case for manual transaxles[m]
- *Chrysler LeBaron (1987):* bumper reinforcements[m]
- *GM GenII 2.8 L V-6 (1987):* front cover, rocker cover, generator mounting bracket and belt tensioner, cylinder heads, and intake manifold[k]
- *GM GenII 2.0 L 4 cylinder (1987):* front cover, rocker cover, elbow on remote air cleaner assembly, air cleaner housing, and cylinder heads[k]
- *AMC 4.0 L 6-cylinder Jeep engine (1987):* engine covers, rocker covers[k]
- *Ford 4.9 L inline 6 cylinder for light trucks (1987):* intake plenum and branch manifold individual runners[k]
- *Chrysler Turbo II 4 cylinder for Dodge Daytona Shelby (1987):* intercooler and dual toned intake manifold[k]
- *Chrysler 3.0 L V-6 (import, 1987):* cylinder heads, rocker arms, and three-piece intake manifolds[k]
- *Oldsmobile Buick LaSabre and Trofero (T-Type), Pontiac Bonneville, Chevrolet Celebrity and Cavalier Z24 (1987):* wheels[k]
- *Ford Econoline van (1987):* driveshaft[k]
- *Cadillac Allante (1987):* stamped body panels—six inner and outer hood, deck lid and removable roof panels[k]
- *Ford 4-wheel-drive Tempo and Topaz (1987):* transfer case[k]

Stainless steel:
- *Chrysler front-wheel-drive car/van lines:* exhaust systems[m]

SOURCES:

[a] *Design News*, Dec. 2, 1985, p. 30.

[b] *American Metal Market*, Aug. 21, 1986, p. 8.

[c] *Popular Science*, July 1985, pp. 50-53.

[d] *Chemical Business*, June 1986, pp. 10-13.

[e] *Iron Age*, Dec. 20, 1985.

[f] *American Metal Market/Metal Working News*, May 19, 1986, p. 1.

[g] *Automotive News*, 1985, p. 1.

[h] *American Metal Market*, Jan. 26, 1986, p. 5.

[i] *Materials Engineering*, October 1985, pp. 28-35.

[j] *Chemtech*, September 1985, p. 556.

[k] *American Metal Market*, Aug. 14, 1986, p. 1.

[l] *Light Metal Age*, December 1985, pp. 16-17.

[m] *American Metal Market/Metal Working News*, July 21, 1986.

[n] *Metal Progress*, May 1986, p. 44.

grilles, and interior panels. Structural applications, using glass and graphite fiber-reinforced matrices, include leaf springs and drive shafts.

For the automakers, using unreinforced plastics and fiberglass composites trims tooling costs (tooling for a steel hood requires 52 weeks; for a fiberglass composite hood, 39 weeks[14]) and allows them to respond quickly to market and competitive changes because of the cost advantages of unreinforced plastics and fiberglass composites at low production volumes. Using these materials also provides increased part durability and decreases the number of necessary parts (e.g., the space frame used in the Fiero has 300 structural steel parts; by using PMCs, this total could be reduced to 30, and 4,000 welds could be eliminated).[15]

New coating technologies, mostly of zincrometal, have improved the corrosion resistance of steel and helped to keep it competitive with noncorroding reinforced plastics. One company has developed an alumina-ceramic coating derived from aerospace products (blades, vanes, and other gas turbine engine hardware) that can be used to protect automobile fasteners from corrosion.[16] HSLA steels offer weight savings over traditional carbon steels due to their higher strength. The use of HSLA steels in automobiles has increased from 5 percent in 1975 to 14 percent in 1985 and is expected to rise above 20 percent by early in the 1990s.[17] Aluminum is generally not considered cost-competitive with either HSLA or mild steel, but it is almost cost-competitive with cast iron. A recent joint venture by an aluminum company and an auto manufacturer produced a prototype aluminum car body that weighed 46.8 percent less than a comparable steel prototype and performed as well as a comparable steel body.[18]

Substitution of lightweight materials in automobiles is at a plateau; most of the easier substitutions have been made, and only those requiring substantial improvements in the technology of alternative materials remain.[19] When the newer unreinforced plastics and PMCs are improved to the point where they can be used in more demanding applications and can be produced economically, materials substitution can occur at a faster rate.

Early estimates by automakers suggested that the usage of lightweight materials would increase significantly by 1991.[20] [21] Such a change in usage would depend heavily on: 1) the concurrent development of lightweight materials technologies and competitive costs, 2) maintenance of the current automotive industry trend toward increased competitiveness, and 3) the acceptance of new materials by car buyers, automakers, and suppliers to the automotive industry.

However, automakers now feel that these early estimates may have been too optimistic by about five years. A plausible scenario might be that composites could displace 3 percent of automotive steel use by the late 1990s.[22] this would mean a decrease in total steel use in the United States of only 0.4 percent by dollar value.

Because aluminum is a lightweight material, there is not as much driving force for substitution by PMCs. However, if PMCs offer other advantages over aluminum, such as lower cost or greater ease of manufacturing, PMCs may begin to substitute for aluminum in automobiles.

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[14] "Fiber-Glass Composites Aim at Autos' Structural Parts," *Iron Age*, Dec. 20, 1985, p. 16.

[15] Ibid.

[16] D.F. Baxter, "Developments in Coated Steels," *Metal Progress*, May 1986, pp. 31-34.

[17] Larson et al., op. cit., footnote 4, p. 38.

[18] "Aluminum Car Bodies in the Future," *Light Metal Age*, December 1985, pp. 16-17.

[19] izatt, op. cit., footnote 1, 1987.

[20] H.E. Chandler, "Material Trends at Mazda Motor Corp.," *Metal Progress*, May 1986, pp. 52-58.

[21] A. Wrigley, "Alloys and New Materials — Auto Industry in Materials Flux: Alloys Outlook Still Optimistic," *American Metal Market*, Feb. 24, 1986, pp. 7, 10.

[22] Ch. 7 presents a scenario of 500,000 PMC automobiles per year in production by the late 1990s. This would cause a drop in automotive steel use of 250,000 tons or about 3 percent.

POTENTIAL FOR SUBSTITUTION IN THE CONSTRUCTION INDUSTRY

New construction represents the fourth largest U.S. market for steel (about 7 percent of total steel output as shown in table 6-2). New construction consumes less than 1 percent of the total U.S. aluminum output.

High-Strength Concrete as a Substitute for Steel

The development and increasing use of high-strength concrete represents a market challenge to both steel structural shapes and steel reinforcing bars. Because of the high compressive strengths of high-strength concrete (defined to be in the range of 84 to 110 megapascals (MPa)) this material can be used in structural applications that would otherwise use structural steel members. High-strength concrete has comparatively low tensile strength, low stiffness, and low toughness, although its toughness is higher than that of lower strength concrete. In addition, it requires less reinforcement than ordinary concrete, thus reducing the need for reinforcing bars.

High-strength concrete, which has been under development for several years, has now entered a high-growth phase. Use of high-strength concrete could increase at a much more rapid rate over the next 5 ~~to 10 years as~~ those various high-strength concretes under laboratory testing are used in actual construction.

The major driving force for using high-strength concrete is its relatively greater ratio of strength to unit cost which makes it the most economical means of carrying compressive forces. Because compressive strength is also higher per unit weight and volume, less massive structural members can be used compared to lower strength concrete. Cost studies have been conducted that show the advantage of using high-strength concrete with a minimum of steel reinforcement.[23]

An example presented in table 6-6 shows that total cost of 33 steel-reinforced concrete columns for a 79-story building would be about $3.8 million for high-strength concrete, compared to approximately $7.7 million for normal-strength concrete.

The major uses for high-strength concrete have been for columns of high rise structures and precast, prestressed bridge girders, although there have also been some special applications in dams, grandstand roofs, piles for marine foundations, decks of dock structures, industrial manufacturing applications, and bank vaults.[24]

Significant improvements in the properties of high-strength concrete can occur over the next 20 years. Research is underway on fibers for a new generation of fiber-reinforced high-strength

Table 6-6.—Cost Comparison of Using Normal and High-Strength Concrete for a 79-Story Building

	Compressive strength	
Materials	High[a] (up to 12,000 psi) (84 MPa)	Normal[b] (4,000 psi) (28 MPa)
Cost per 25 × 25 ft. panel		
Concrete	$ 45,035	$ 88,836
Forms	35,729	54,606
Longitudinal steel	34,449	87,161
Spirals	1,441	1,930
Total	$116,654	$232,533
Total cost for 33 columns	$3,849,582	$7,673,589

[a] With the high-strength concrete, column dimensions were kept constant and were calculated so that the lowest story columns can be made with a 12,000 psi (84 MPa) concrete and 1 percent longitudinal steel. The dimensions of the column and the percentage of the longitudinal steel was maintained constant for all 79 stories. The top 29 floors were designed with 4,000 psi (28 MPa), the next 31 floors with 9,000 psi (63 MPa), while the bottom 19 floors were designed with 12,000 psi (84 MPa).

[b] For normal strength concrete, all floors had concrete with a compressive strength of 4,000 psi (28 MPa). However, to maintain a 1 percent ratio of the longitudinal steel, the dimensions of the designed circular columns were increased from 1,400 mm at the top to 2,950 mm for the bottom story.

SOURCE: S.P. Shah, P. Zia, and D. Johnston, "Economic Consideration for Using High Strength Concrete in High Rise Buildings," a study prepared for Elborg Technology Co., December 1983. As presented in: S.P. Shah and S.H. Ahmad, "Structural Properties of High Strength Concrete and Its Implications for Precast Prestressed Concrete," *Prestressed Concrete Institute Journal* 30(6):109-110, November-December 1985.

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[23] ACI Committee 363, "State of the Art Report on High Strength Concrete," ACI 363R-84, *ACI Journal*, July-August 1984, pp. 366-367.

[24] Ibid., pp. 403-404.

concretes. As this technical improvement occurs, construction markets originally dominated by steel could become potential markets for the new concrete. Assuming from the example in table 6-6 that 60 percent less steel (by dollar value) is needed to reinforce high-strength concrete building columns, and that this figure could be used as an estimate for the decrease due to substitution in total construction use of steel (7 percent by dollar value), this would mean a decline in total steel use by a dollar value of about 4 percent.

PMCs and Unreinforced Plastics as Substitutes for Steel and Aluminum

PMCs are highly unlikely to substitute for steel or aluminum in the construction industry to a significant degree in the foreseeable future. The cost of PMCs is prohibitive compared to other construction materials. Steel, cement, and concrete sell for dollars per ton, whereas PMCs that have matured in their processing technology (e.g., fiberglass/epoxy) sell for dollars per pound. As with high-strength concrete, the general lack of familiarity with the properties of PMCs as well as the highly fragmented nature of the construction industry tends to retard their widespread adoption. However, in the long term, PMCs may find limited use in specialized applications such as nonmetallic, nonmagnetic structures, bridges, and manufactured housing (see ch. 3).

Unlike PMCs, unreinforced plastics have the potential to displace significant amounts of metal (mainly aluminum) in the construction industry. Sales of unreinforced plastics to the construction market rose from 2,354 million metric tons in 1974 to 4,212 metric tons in 1984, an increase of nearly 80 percent. Sales are expected to grow an additional 25 percent by 1990, to 5,265 million metric tons.[25] These figures highlight the overall trend in the construction market toward using unreinforced plastics. Unreinforced plastics compete directly with aluminum in those applications that require little load bearing capability such as window frames, doors, and screens.

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[25] J.A. Schlegel, *Barrier Plastics: The Impact of Emerging Technology*, AMA Management Briefing, American Management Association, 1985, p. 43.

POTENTIAL FOR SUBSTITUTION IN THE CONTAINER INDUSTRY

Containers and packaging constitute the third largest market segment for aluminum (see table 6-3) and the seventh largest market segment for steel (see table 6-2). The large majority of rigid containers are used for the primary packaging of beer, food, and soft drinks. Total rigid container shipments increased at an average annual rate of 1.4 percent during the 1974-84 period; this represents 19.6 billion containers.[26] However, because the food and beverage segments of the container market have reached maturity, the growth for any one material must come at the expense of another.

The container market represents a competition among several materials: aluminum, steel, unreinforced plastics, and glass. With respect to beverage containers, both aluminum and steel are in the mature phase of their technology development. In contrast, unreinforced plastics for the soft drink market are still relatively new technologies. To compete in the soft drink market, plastic containers are required to have barrier properties to protect the container contents against permeation of gases (e.g., oxygen, carbon dioxide, and water vapor), degradation due to light (especially ultraviolet light), aroma/odor changes, and effects of organic chemicals and hydrocarbons. Aluminum, steel, and glass provide an "ultimate barrier" against these possibilities.

There are a number of driving forces for the adoption of unreinforced plastics in those markets currently served by metal containers. These include potential for processing savings; shipment and storage savings (aseptic products made of plastic can be shipped and stored without refrigeration); consumer preference for convenience packaging that allows a container to be used easily, e.g., taken from freezer to microwave (or conventional oven) and thence to the table. The fact that some barrier plastics can be recycled may also be a driving force for adopting unreinforced plastics for containers and packaging. It is estimated that 100 million pounds, or about 19 percent of the total annual polyethyleneterephthalate (PET) production of 535 million pounds was recycled in 1984.[27]

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[26] U.S. Department of Commerce, *1985 U. S. Industrial Outlook*, January, 1985, Washington, DC, p. 6-1.

Over the short term (2 to 5 years), aluminum could face a continually increasing competitive threat from unreinforced plastics in the single-serve soft drink market. Unreinforced plastics would not substitute directly for aluminum in the short term, but they could continue to displace glass in half-liter sizes and hence offer consumers a choice of the plastic container as an alternative to the 12-ounce can. These competitive forces do not constitute substitution of unreinforced plastics for aluminum; rather, this situation would hold the demand for cans under what it normally would have been, thereby decreasing the overall growth of the market for aluminum.

In the longer term (5 to 10 years), the recyclability of unreinforced plastics versus aluminum will be an important consideration, as will the relative weight of the two materials since weight affects processing, shipping, and storage costs. Although the current plastic material, PET, is recyclable (the recycled product goes into converting textile fiber-fill, strapping, plastic lumber, and polyols for other polymer manufacture), this is not the material that would substitute directly for the aluminum beverage can. The plastic or plastic composite can (i.e., a can made of combined layers of plastic with special barrier properties) could be made of more than one type of plastic and hence could make recycling much more difficult.

Since the technology for aluminum food cans is still in a beginning stage, there could be significant advances over the next 10 to 20 years that could increase the aluminum can's competitive position. Aluminum's share of the food can market could increase to about 10 to 15 percent over the next 15 years.[28]

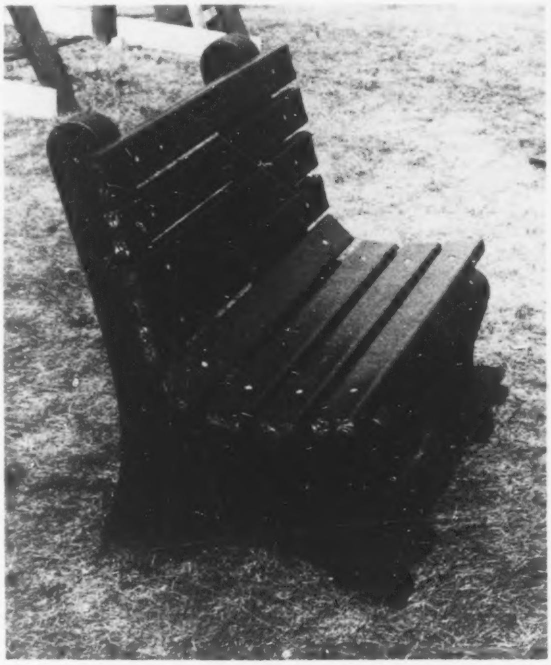

Photo courtesy of Processed Plastics Co.

Plastalloy bench made of 100% recycled plastic.

The current trend toward alternative containers could continue to become very significant in the 3- to 10-year time frame, and unreinforced plastics could be the dominant materials for food cans. The substitution of unreinforced plastics for aluminum in beverage containers could begin in a significant way in the 3- to 10-year time frame and become a potentially serious competitor to aluminum in the 5- to 15-year time frame.

Assuming that in 15 years unreinforced plastics will capture half of all container markets for aluminum (currently 7 percent by dollar value of all aluminum use), total U.S. aluminum use could decrease by 3 to 4 percent by dollar value. Total container use of steel is currently 4 percent of the total steel output by dollar value, and use of steel is likely to decrease significantly as both aluminum and unreinforced plastics substitute for steel in containers.

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[27] *1986 Beverage Industry Annual Manual*, produced by Magazines for Industry, Harcourt, Brace, Jovanovich Publications, September 1986, p. 62.

[28] Alcoa 1985 Annual report.

DEVELOPMENT OF NEW INDUSTRIES AND CHANGES IN EXISTING INDUSTRIES

Substitution has the potential to become a significant force over the next 20 years as new materials technologies are commercialized. This assessment, however, is contingent on the ability of these materials to overcome key technical and economic barriers that are identified in this report.

To the present time, there have been two effects of materials substitution on the steel and aluminum industries: an increase in R&D aimed specifically at efforts to develop new materials; and inter- and intra-industry joint ventures aimed at new product development in traditional as well as advanced materials.

Intra-industry cooperative efforts in the steel industry have centered on developing a new direct sheet casting process and on electrogalvanizing (EG) lines. These efforts are being undertaken jointly (primarily due to a lack of individual company resources) as responses to a recognized materials substitution threat. The installation of EG lines is in direct response to more stringent automaker requirements concerning corrosion and surface quality, and represent the steelmakers' strategy to ward off competition from other metals and unreinforced plastics.[29] The commitment to this strategy can be seen by the fact that five new lines came on stream in 1986 representing a $500 million investment, and that there are 13 coatings for automotive sheet steel now being produced.[30]

There have been several joint ventures between aluminum user and supplier industries including one to develop and make high-performance plastic containers for the U.S. food industry, and one with a foreign automaker for the development of a prototype aluminum auto body and frame. These efforts are direct responses by the aluminum industry to the materials substitution threat and the potential for aluminum to substitute for steel in automobiles.

In addition to diversifying into nonmetals businesses, the aluminum industry is pursuing opportunities in Al-Li alloys, MMCs, and rapidly solidified technology. Currently, for instance, four aluminum firms either have or are anticipating having plants to produce Al-Li alloys. Because Al-Li alloys are sold to the same markets as traditional aluminum, aluminum firms have a strong marketing advantage over new firms. The widespread use of Al-Li alloys could also cause significant modifications to the end users of these new alloys.

Because lithium is poisonous even at very low concentrations, special precautions must be taken to segregate Al-Li scrap from other aluminum scrap that would be recycled by usual methods. Because of the special precautions that must be taken, specialized machine shops and recycling centers could be required.

Alcoa is developing its aramid-reinforced aluminum MMC (ARALL) to be used on commercial aircraft and Dural Aluminum Composites Corp. (a wholly owned subsidiary of Alcan Aluminum) brought 2 to 3 million pounds of capacity for silicon carbide-reinforced aluminum MMC on line in February 1988.[31]

Significant substitution of advanced materials for aluminum and steel in the various markets mentioned above could occur in roughly 10 to 30 years after substitution has begun, based on past experience in these or similar industries. As these materials begin to substitute for aluminum and steel, new industries will be formed.

PMCs and Unreinforced Plastics Industries

The PMC and unreinforced plastics industries have already established definite market segments. Significant growth in sales of PMCs is expected. Charles H. Kline & Co. estimates that the demand for PMCs in automobiles could rise from approximately 700,000 pounds in 1984 to 1.4 million pounds in 1995, and the demand for PMCs in aircraft/aerospace applications could increase from approximately 8.6 million pounds in 1984 to nearly 75 million pounds in 1995.[32] This study projects that sales of PMCs will reach approximately $5.5 billion by the year 2000.[33] Overall, about 3 percent of total U.S. resin production is used in some type of composite.[34]

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[29] Wrigley, op. cit., footnote 21, 1986.

[30] T. Cirisafulli, "Industry Striving for Better Steels to Battle Competition in Auto Market," *American Metal Market*, Mar. 11, 1986, p. 3.

[31] "Alcan's Dural Unit to Expand Aluminum Composite Capacity," *Performance Materials* (Washington, DC: McGraw-Hill, Jan. 11, 1988), p. 2.

Adhesives and Coating Industries

Increased growth in PMC materials could also increase the demand for specialty adhesives and coatings. C.H. Kline & Co. forecasts that demand for specialty adhesives and coatings for PMCs could grow from $35 million in 1985 to $110 million in 1995, an average rate of growth of 12.1 percent per year.[35] Liquid, paste, and film adhesives together accounted for 85 percent of the total dollar value of adhesives markets in 1985.

The current adhesives and coatings industry structure is fairly concentrated, with American Cyanamid, Ashland, 3M, and Morton-Thiokol together controlling about 60 percent of the market. However, the industry may become less concentrated over the long term as other suppliers strive to increase their presence.

Weaving Industry

PMCs using three-dimensional braided fibers or woven fabrics offer a significant advantage over unidirectional tape or two-dimensional prepreg, in that there is less tendency for the PMC structure to delaminate under loading. Although the number of companies now producing these braided structures is small, their numbers could grow as the demand for braided PMCs increases. This industry could grow quickly over the next 10 to 20 years because of expected increases in the use of braided preforms for PMCs and MMCs, especially in the aircraft industry.

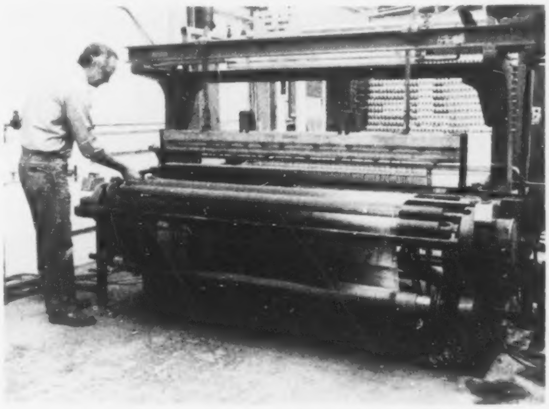

Photo courtesy of AVCO Specialty Materials

Flexible interweaving of SiC-reinforced Al to be used in investment casting process.

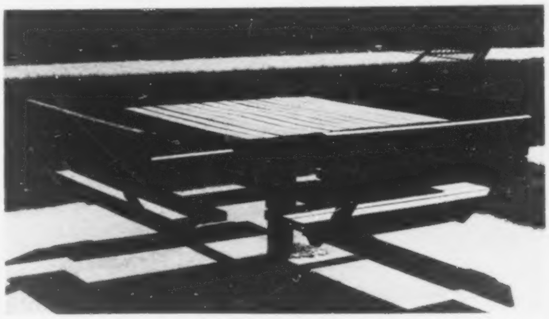

Photo courtesy of Polymer Products, Inc.

Integrated benches and table made from 100% recycled plastics.

Recycling Industry

Disposal of unreinforced plastics and PMCs currently pose large problems; several States now have legislation pending to ban nondegradable plastic products such as six-pack rings, fast food packaging, and egg cartons.[36] However, no viable technologies currently exist for degradable plastics food packaging.[37] More and more, companies are beginning to look toward recyclable plastics. The fact that thermosets such as epoxies are not recyclable may make them obsolete, according to some industry experts.[38] Reinforced or layered plastics may prove to be a major problem to recycling efforts, sufficient to inhibit their use, according to some recycling industry representatives.[39]

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[32] S. Brown, C.H. Eckert, and C.H. Kline, "Advanced Polymer Composites: Five Keys to Success," presented to the Suppliers of Advanced Composite Materials Association (SACMA), in Anaheim, CA, Mar. 21, 1985.

[33] Ibid.

[34] Norman Fishman, SRI International, personal communication, May 1988.

[35] "Adhesives, Coatings Makers Banking on Composites Growth," *Chemical Marketing Reporter*, July 21, 1986, pp. 7, 26.

[36] Robert Leaversuch, "Industry Weighs Need to Make Polymers Degradable," *Modern Plastics*, August 1987, p. 53.

[37] Ibid.

Three changes could occur in the recycling industry. First, since recycling of aluminum cans has become a significant activity over the past 15 years, the aluminum recycling industry could be seriously affected as the use of aluminum in beverage cans decreases. It is possible, however, that the recyclability of aluminum could give the metal a significant advantage over competing materials that cannot be easily recycled, e.g., unreinforced plastics and PMCs.

The second change could occur in the steel recycling industry. The increasing use of nonrecyclable materials in uses traditionally served by steel could have adverse effects on the recycling industry, especially in the case of automobiles, in that scrap steel is reused in electric furnaces.

The third change could be the emergence of specialty recycling facilities that can handle poisonous materials (e.g., aluminum alloys containing lithium) or difficult-to-recycle materials (e.g., unreinforced plastics, MMCs, or PMCs). There currently exists no satisfactory commercial process to recycle these materials. However, recycling processes are now under development, and it is possible that commercially viable processes could be put into use as the growth of these materials industries proceeds.

In summary, the substitution of new materials for aluminum and steel in major market segments could create significant new industries and modifications to existing industries over the next two decades. Secondary industries such as the adhesives, coatings, weaving, and recycling industries could also be affected as new materials are increasingly adopted. The recyclability of the new materials could become a major factor affecting their use.

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[38] Robert Leaversuch, "Practicality is the Key in New Strategies for Recycling," *Modern Plastics*, August 1987, p. 67.

[39] Ibid.

Chapter 7

Case Study: Polymer Matrix Composites in Automobiles

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Chapter 7

Case Study: Polymer Matrix Composites in Automobiles

FINDINGS

The increased use of advanced structural materials may have significant impacts on basic manufacturing industries. The automotive industry provides an excellent example, since it is widely viewed as being the industry in which the greatest volume of advanced composite materials, particularly polymer matrix composites (PMCs), will be used in the future. Motivations for using PMCs include weight reduction for better fuel efficiency, improved ride quality, and corrosion resistance. Extensive use of composites in automobile body structures would have important impacts on methods of fabrication, satellite industry restructuring, and creation of new industries such as recycling.

The application of advanced materials to automotive structures will require: 1) clear evidence of the performance capabilities of the PMC structures, including long-term effects; 2) the development of high-speed, reliable manufacturing and assembly processes with associated quality control; and 3) evidence of economic incentives (which will be sensitively dependent on the manufacturing processes).

The three performance criteria applicable to a new material for use in automotive structural applications are fatigue (durability), energy absorption (in a crash), and ride quality in terms of noise, vibration, and harshness (generally related to material stiffness). There is emerging evidence from both fundamental research data and field experience that glass fiber-reinforced PMCs can be designed to fulfill these criteria.

At present, the successful application of PMCs to automobile body structures is more dependent on quick, low-cost processing methods and materials than it is on performance characteristics. There are several good candidate methods of production, including high-speed resin transfer molding, reaction molding, compression molding, and filament winding. At this time, no method can satisfy all of the requirements for production; however, resin transfer molding seems the most promising.

Clearly, the large-scale adoption of PMC construction for automobile structures would have a major impact on fabrication, assembly, and the supply network. The industry infrastructure of today would completely change; e.g., the multitude of metal-forming presses would be replaced by a much smaller number of molding units, multiple welding machines would be replaced by a limited number of adhesive bonding fixtures, and the assembly sequence would be modified to reflect the tremendous reduction in parts. This complete revamping of the stamping and body construction facilities would clearly entail a revolution (albeit at an evolutionary pace) in the industry. However, there would probably not be a significant impact on the size of the overall labor force or the skill levels required.

Extensive use of PMCs by the automotive industry would necessitate the development of completely new supply industries geared to providing inexpensive structures. It is anticipated that such developments would take place through two mechanisms. First, current automotive suppliers, particularly those with plastics expertise, would unquestionably expand and/or diversify into PMCs to maintain and possibly increase their current level of business. Second, the currently fragmented PMCs industry, together with raw material suppliers, would generate new integrated companies with the required supply capability. In addition, completely new industries would have to be developed, e.g., a comprehensive network of PMC repair facilities, and a recycling industry based on new technologies.

Economic justifications for using PMCs in automotives are not currently available. The economics will not become clear until the manufacturing developments and associated experience are in hand. Economics, customer perception, and functional improvements will dictate the eventual extent of usage. Present economic indicators suggest that PMCs would initially be used only for low-volume vehicles, and thus the most likely scenario would be limited usage of these materials. It is clear that a significant fraction of annual U.S. auto production would have to convert to large-scale PMC usage before a major impact is felt by such related industries as the steel industry, tool and die manufacturers, and chemical manufacturers. For example, it would take production of 500,000 largely-PMC vehicles per year to cause a 3 percent decrease in automotive steel use. The corresponding effect on these industries, therefore, would be minor.

INTRODUCTION

The use of PMC materials in the United States in automotive applications has gradually evolved over the past two decades. With new materials and processing techniques being continuously developed within the U.S. plastics and automotive industries, there is potential for a more rapid expansion of these types of applications in the future. PMC applications, both for components and for major modular assemblies, appear to be a potential major growth area that could have a significant impact on the U.S. automotive industry and associated supply industries if the required developments result in cost-effective manufacturing processes.

Extensive research and development (R&D) efforts currently underway are aimed at realizing eight potential benefits of PMC structures for the U.S. automotive industry:

- weight reduction, which may be translated into improved fuel economy and performance;
- improved overall vehicle quality and consistency in manufacturing;
- part consolidation resulting in lower vehicle and manufacturing costs;
- improved ride performance (reduced noise, vibration, and harshness);
- vehicle style differentiation with acceptable or reduced cost;
- lower investment costs for plants, facilities, and tooling—depends on cost/volume relationships;
- corrosion resistance; and
- lower cost of vehicle ownership.

However, there are areas where major uncertainties exist that will require extensive research and development prior to resolution. For example:

- high-speed, high-quality manufacturing processes with acceptable economics;
- satisfaction of all functional requirements, particularly crash integrity and long-term durability;
- repairability;
- recyclability; and
- customer acceptance.

The purpose of this case study is to present scenarios showing the potential impact of PMCs on the U.S. automotive industry, its supplier base, and customers. These scenarios depict the effects likely to be generated by implementation of the types of materials and process techniques that could find acceptance in the manufacturing industries during the late 1990s, provided development and cost issues are favorably resolved.

To project the potential of PMCs for automotive applications, it is necessary to provide a reasonably extensive summary of the current state of these materials from the U.S. automotive industry's perspective. In particular, the specific types of PMCs showing the most promise for structural applications are described, as well as the most viable fabrication processes. The particular properties of greatest relevance to automotive applications are presented, together with an agenda for gaining the knowledge required before high confidence can be placed in the structural application of the materials.

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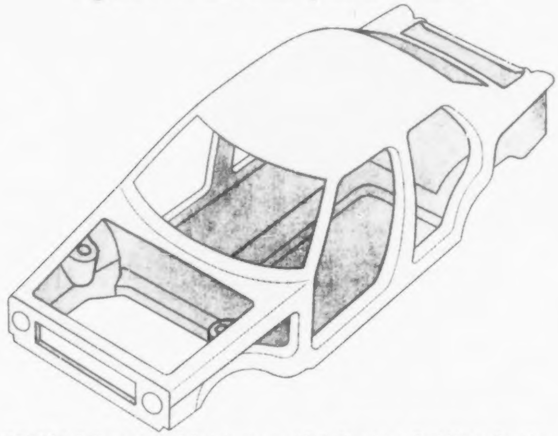
[1] This chapter is based on a contractor report prepared for the Office of Technology Assessment, by P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., entitled "Impact of New Materials on Basic Manufacturing Industries—Case Study: Composite Automobile Structure," 1987.

This case study illustrates the potential of PMCs by examining the case of a highly integrated PMC body shell, as depicted in figure 7-1. Basically, this body shell is the major load-bearing structure of the automobile. This basic structure, which does not include the hood, decklid, and doors, has been chosen as representative of the type of assembly that might be produced in moderate volumes as PMC materials begin to penetrate the U.S. automobile industry.

Figure 7-1.—Steel Body Shell Structure



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

BACKGROUND

The economic constraints in a mass-production industry such as the automotive industry are quite different from the aerospace or even the specialty-vehicle industry. This is particularly true in the potential application of high-performance PMC materials, which to date have primarily been developed and applied in the aerospace industry. At present, virtually all uses of plastics and PMCs in high-volume vehicles are restricted to decorative or semistructural applications.

Sheet molding compound (SMC) materials are the highest performance composites in general automotive use for bodies today. However, the most widely used SMC materials contain about 25 percent chopped glass fibers by weight and cannot really be classified as high-performance composites. Typically, SMC materials are used for grille-opening panels on many auto lines and closure panels (hoods, decklids, doors) on a few select models.

The next major step for PMCs in the automotive business is extension of usage into truly structural applications such as the primary body structure, and chassis/suspension systems. These are the structures that have to sustain the major road-loads and crash loads. In addition, they must deliver an acceptable level of vehicle dynamics such that the passengers enjoy a comfortable ride.

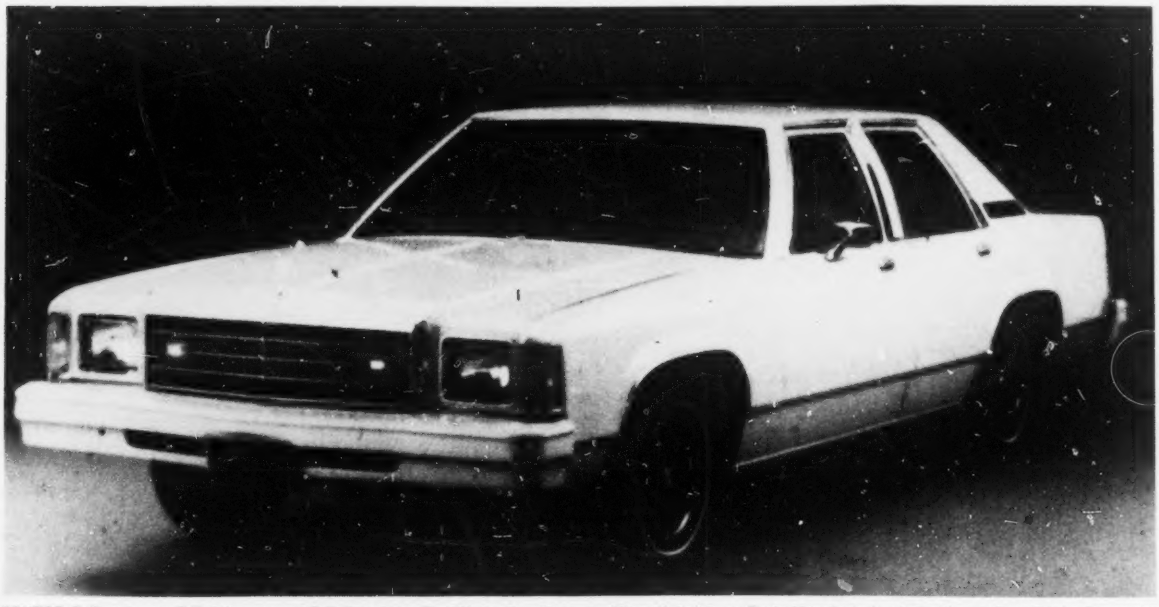
These functional requirements must be totally satisfied for any new material to find extensive application in body structures, and it is no small challenge to PMCs to meet these criteria effectively. These criteria must also be satisfied in a cost-effective manner. Appropriate PMC fabrication procedures must be applied or developed that satisfy high production rates but still maintain the critical control of fiber placement and distribution.

PMC body structures have been used in a variety of specialty vehicles for the past three decades; Lotus cars are a particularly well-known example. The PMC reinforcement used in these specialty vehicles is invariably glass fiber, typically in a polyester resin. A variety of production methods have been used but perhaps the only thing they have in common is that all the processes are slow, primarily because of the very low production rate of vehicles (typically, up to a maximum of 5,000 per year).[2] Thus, there has been no incentive to accelerate the development of these processes for mass production. The other common factor among these specialty vehicles is the general use of some type of steel backbone or chassis, which is designed to absorb most of the road loads and crash impact energy. Thus, while the composite body can be considered somewhat structural, the major structural loads are not imposed on the composite materials.

Current vehicles that include high volumes of fiber-reinforced plastic (FRP) have been designed specifically for FRP materials, as opposed to being patterned after a steel vehicle. Consequently, it is not possible to make a direct comparison between an FRP vehicle and an identical steel vehicle to derive baseline characteristics. Perhaps the best comparison would be between the prototype "Graphite LTD" built by Ford, and a production steel vehicle.[3] The vehicle was fabricated by hand lay-up of graphite fiber prepreg.

This graphite fiber-reinforced plastic (GrFRP) auto is shown in figure 7-2, and an exploded schematic showing its composite parts is presented in figure 7-3. The weight savings for the various structures are given in table 7-1. While these weight savings (of the order of 55 to 65 percent) might be considered optimal because of the use of low density graphite fibers, other more cost-effective fibers are stiff enough to be able to achieve a major portion of these weight savings (with redesign).[4] Although the GrFRP vehicle weighed 2,504 pounds compared to a similar steel production vehicle of 3,750 pounds, vehicle evaluation tests indicated no perceptible dif-

Figure 7-2.—Ford Graphite Fiber Composite (GrFRP) Vehicle



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

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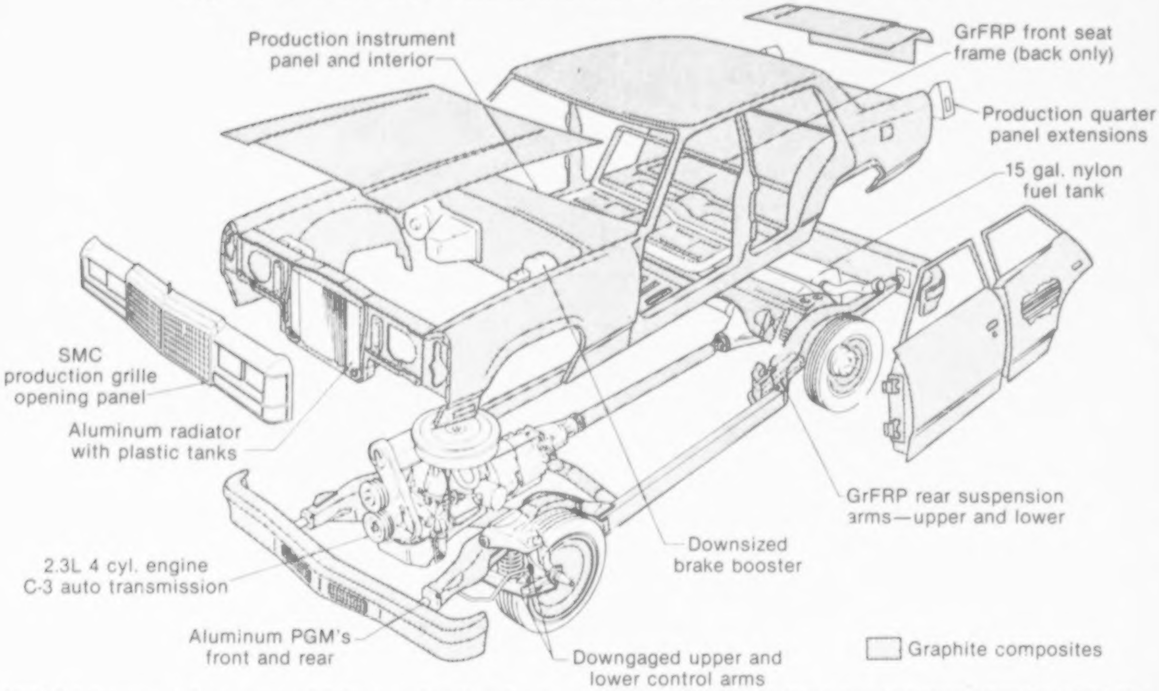
[2] Ibid.

[3] P. Beardmore, J.J. Harwood, and E.J. Horton, paper presented at the International Conference on Composite Materials, Paris, August 1980.

[4] Beardmore, Johnson, and Strosberg op. cit., footnote 1.

Figure 7-3.—Ford GrFRP Vehicle With the Composite Components Shown


Production instrument panel and interior
GrFRP front seat frame (back only)
Production quarter panel extensions
15 gal. nylon fuel tank
SMC production grille opening panel
Aluminum radiator with plastic tanks
GrFRP rear suspension arms—upper and lower
Downsized brake booster
2.3L 4 cyl. engine C-3 auto transmission
Aluminum PGM's front and rear
Downgaged upper and lower control arms
▭ Graphite composites

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

ference between the vehicles.[5] The GrFRP auto's ride quality and vehicle dynamics were judged at least equal to those of top-quality production steel LTD autos. Thus, on a direct comparison basis, a vehicle with an entire FRP structure was proven at least equivalent to a steel vehicle from a vehicle dynamics viewpoint at a weight level only 67 percent of the steel vehicle.[6]

The GrFRP auto clearly showed that high-cost fibers (graphite) and high-cost fabrication tech-

Table 7-1.—Major Weight Savings of GrFRP[a] Over Steel in Ford "Graphite LTD" Vehicle Prototype

	Weight in pounds		
Component	Steel	GrFRP	Reduction
Body-in-white	423.0	160.0	253.0
Front end	95.0	30.0	65.0
Frame	283.0	206.0	77.0
Wheel(s)	91.7	49.0	42.7
Hood	49.0	17.2	32.3
Decklid	42.8	14.3	28.9
Doors (4)	141.0	55.5	85.5
Bumpers (2)	123.0	44.0	79.0
Driveshaft	21.1	14.9	6.2
Total vehicle	3750	2504	1246

[a] GrFRP = Graphite Fiber-Reinforced Plastic.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7-2.—Crash Energy Absorption Associated With Fracture of Composites Compared With Steel (typical properties)

Material	Relative energy absorption (per unit weight)
High performance composites[a]	100
Commercial composites[b]	60-75
Mild steel	40

[a] For example, graphite fiber-reinforced.
[b] For example, glass fiber-reinforced.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

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[5] Ibid.

[6] Ibid.

niques (hand lay-up) can yield a vehicle that is wholly acceptable in terms of handling, performance, and vehicle dynamics. However, crash and durability performance were not demonstrated, and these issues will need serious development work to achieve better-than-steel results. An even bigger challenge is to translate the GrFRP auto's performance into realistic economics through the use of cost-effective fibers, resins, and fabrication procedures.

Specialty autos of high PMC content use steel as the major load-carrying structure and are not generally priced on a competitive basis. Consequently, these vehicles cannot be used to develop guidelines for extensive PMC usage in high-volume applications.

The governing design guidelines for PMCs need to be further developed to ascertain, for instance, how to design using low-cost PMC materials, and to ascertain allowables for stiffness in situations where major integration of parts in PMCs eliminates a myriad of joints. The following sections summarize information on composite materials, performance criteria, and potential manufacturing techniques.

POLYMER MATRIX COMPOSITE MATERIALS

By far the most comprehensive property data have been developed on aerospace-type PMCs, in particular graphite fiber-reinforced epoxies fabricated by hand lay-up of prepreg materials. Relatively extensive databases are available on these materials, and it would be very convenient to be able to build off this database for less esoteric applications such as automobile structures. Graphite fibers are the favored choice in aerospace because of their superb combination of stiffness, strength, and fatigue resistance. Unfortunately for the cost-conscious mass-production industries, these properties are attained only at significant expense. Typical graphite fibers cost in the range of $25 per pound. There are intensive research efforts devoted to reducing these costs by using a pitch-based precursor but the most optimistic predictions are for fibers in the range of $5 to 10 per pound, which would still keep them in the realm of very restricted potential for consumer-oriented industries.[7]

The fiber with the greatest potential for automobile structural applications is E-glass fiber—currently, $0.80 per pound—based on the optimal combination of cost and performance.[8] Similarly, the resin systems likely to dominate at least in the near term are polyester and vinyl-ester resins based primarily on a cost/processability trade-off versus epoxy. Higher performance resins will only find specialized applications (in much the same way as graphite fibers), even though their ultimate properties may be somewhat superior.

The form of the glass fiber used will be very application-specific, and both chopped and continuous glass fibers should find extensive use. Most structural applications involving significant load inputs will probably use a combination of both chopped and continuous glass fibers with the particular proportions of each depending on the component or structure. Because all the fabrication processes likely to play a significant role in automotive production are capable of handling mixtures of continuous and chopped glass, this requirement should not present major restrictions.

One potential development likely to come about if glass fiber PMCs come to occupy a significant portion of the structural content of an automobile is the tailoring of glass fibers and corresponding specialty resin development. The size of the industry (each pound of PMC per vehicle translates into approximately 10 million pounds per year in North America) dictates that it would be economically feasible to have fiber and resin production tailored exclusively for the automotive market.[9] The advantage of such an approach is that these developments will lead to incremental improvements in specific PMC materials, which in turn should lead to increased applications and increased cost-effectiveness.

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[7] Ibid.

[8] Ibid.

[9] Ibid.

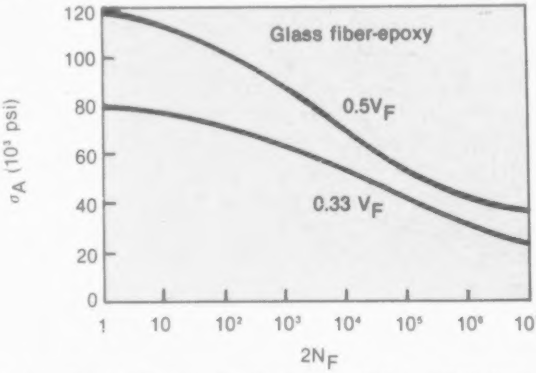
Although thermoset matrix PMCs will probably constitute the bulk of the structural applications, thermoplastic-based PMCs formed by a compression molding process may well have a significant but lesser role to play.

Most of the compression-molded thermoplastics in commercial use today tend to concentrate on polypropylene or nylon as the base resin. The reason is simply the economic fact that these materials tend to be the least expensive of the engineering thermoplastics and are easily processed. Both of these materials are somewhat deficient in heat resistance and/or environmental sensitivity relative to vehicle requirements for high-performance structures.

Other thermoplastic matrices for glass fiber-reinforced PMCs are under development, and materials such as polyethyleneterephthalate (PET) hold significant promise for the future. The extent to which thermoplastic PMCs will be used in future structures will be directly dependent on material developments and the associated economics.

PERFORMANCE CRITERIA

Figure 7-4.—Typical Fatigue Curves for Unidirectional Glass Fiber Composite (GlFRP) as a Function of Volume Fraction of Glass Fibers (V_F)



σ_A is defined as the amplitude of the cyclicly applied stress. N_F is the number of cycles to failure.

Fatigue is described by the number of cycles to failure at a given cyclicly applied stress.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

From a structural viewpoint, there are two major categories of material response critical to applying PMCs to automobiles. These are fatigue (durability) and energy absorption. In addition, there is another critical vehicle requirement, ride quality, which is usually defined in terms of noise, vibration, and ride harshness, and is generally perceived as directly related to vehicle stiffness and damping. Material characteristics play a significant role in this category of vehicle response. These three categories will be discussed below.

Fatigue

The specific fatigue resistance of glass fiber-reinforced plastics (GlFRP) is a sensitive function of the precise constitution of the material. However, there are also preliminary research indications of the sensitivity to cyclic stresses. (For a further discussion of chopped and continuous glass fibers, see ch. 3.)

For unidirectional GlFRP materials, the fatigue behavior can be characterized as illustrated in figure 7-4. The most important characteristic in figure 7-4 is the fairly well-defined fatigue limit exhibited by these materials; as a guiding principle this limit can be estimated as approximately 35 to 40 percent of the ultimate strength.[10] A chopped glass PMC, by contrast, would have a fatigue limit closer to 25 percent of the ultimate strength and tends to produce less reliable fatigue test data. Figure 7-5 shows the scatter in fatigue test data for SMC.[11] [12]

It is also important to note that the different failure modes in PMCs (in comparison to metals) can

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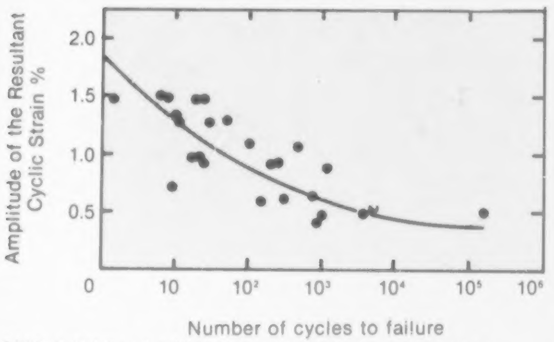
[10] C.K.H. Dharan, *Journal of Materials Science*, vol. 10, 1975, pp. 1665-70.

[11] T.R. Smith and M.J. Owen, *Modern Plastics*, April 1969, pp. 124-29.

[12] A. Potem and Z. Hashim, *AIAA Journal*, vol. 14, 1976, pp. 868-72.

Figure 7-5.—Typical Fatigue Curve for Sheet Molding Compound



SMC exhibits significant scatter in fatigue test data.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

result in different design criteria for these materials, depending on the functionality involved. For instance, a decrease in stiffness can occur under cyclic stressing long before physical cracking and strength deterioration occur. If stiffness is a critical part of the component function, the loss in stiffness under the cyclic road loads could result in loss of the stiffness-controlled function with no accompanying danger of any loss in mechanical function. This phenomenon does not occur in steel.

As a guiding principle, it follows from the above that wherever possible, automotive structures should be designed such that continuous fibers take the primary stresses and chopped fibers should be present to develop some degree of isotropic behavior. It is critical to minimize the stress levels, particularly fatigue stresses, that have to be borne by the chopped fibers.

There is emerging evidence from both fundamental research data and field experience with PMC components that glass fiber-reinforced PMCs can be designed to withstand the rigorous fatigue loads experienced under vehicle operating conditions. The success of PMC leaf springs and SMC components attests to the capability of PMCs to withstand service environments.

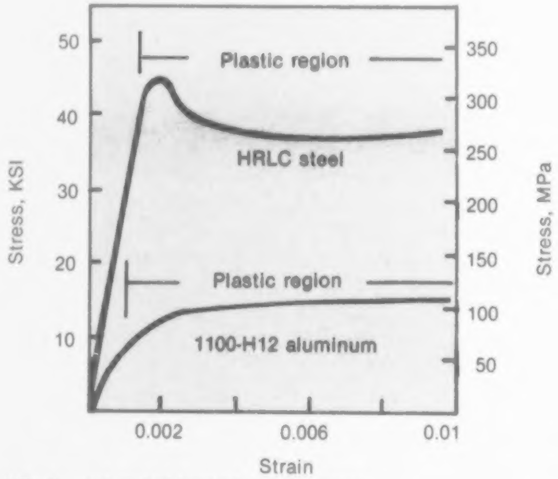
Although the data for all combinations of PMC materials are not yet available, a sufficient database is available such that conservative estimates can be developed and lead to reliable designs. It should be emphasized, however, that the mechanical properties of PMCs (much more than isotropic materials) are very sensitive to the fabrication process. It is imperative that properties be related to the relevant manufacturing technique to prevent misuse of baseline data.

Energy Absorption

The elongation (strain) behavior of a material under stress can indicate a great deal about the material's ability to absorb crash energy. Metals exhibit linear stress-strain behavior only up to a certain point, beyond which they plastically deform (see figure 7-6). This plastic deformation absorbs a large amount of crash energy that could otherwise injure passengers.

The stress-strain curves of all high-performance PMCs are essentially linear in nature, as shown in figure 7-7. This resembles the behavior of brittle materials such as ceramics. Materials that are es-

Figure 7-6.—Tensile Stress-Strain Curves for Steel and Aluminum

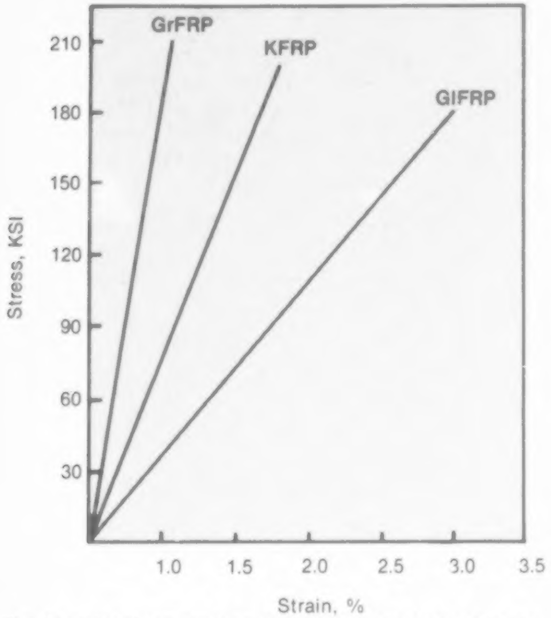


HRLC—hot rolled leaded carbon steel
1100-H12—strain hardened low alloy aluminum

The plastic region of metal stress-strain behavior absorbs crash energy.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-7.—Tensile Stress-Strain Curves for Graphite Fiber Composite (GrFRP), Kevlar Fiber Composite (KFRP), and Glass Fiber Composite (GlFRP)



The linearity of the curves means that these composites behave as brittle materials during fracture (cf fig. 7-6). There is no plastic region to absorb crash energy.

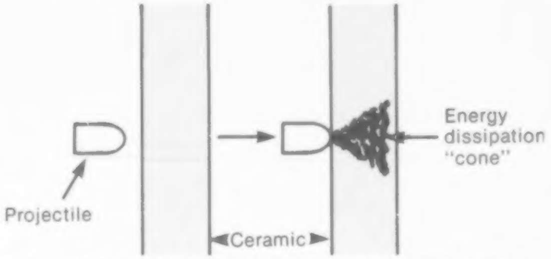
1 KSI = 10^3 psi

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

sentially elastic to failure (PMCs, ceramics) might be thought to have no capacity for energy absorption since no energy can be absorbed through plastic deformation. However, ceramics have been used for decades as armored protection against high-velocity projectiles.

In fact, energy absorption is achieved by spreading the localized impact energy into a high-volume cone of fractured ceramic material, as shown schematically in figure 7-8. A large amount of fracture surface area is created by fragmentation of the solid ceramic, and the impact energy is converted into surface energy resulting in successful protection and very efficient energy dissipation. Brittle materials can be very effective energy absorbers, but the mechanism is fracture surface energy rather than plastic deformation.

Figure 7-8.—Energy Dissipation Mechanism in Ceramics



Energy absorption occurs in ceramics and brittle PMCs by spreading local impact energy into a high-volume cone of fractured material.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

This analogy leads directly to the conclusion that high-performance PMCs may well be able to absorb energy by a controlled disintegration (fracture) process.

Evidence is emerging from laboratory test data on the axial collapse of PMC tubes that efficient energy absorption needed for vehicle structures can be achieved in these materials. A comparison between the collapse mechanisms of metals and PMCs is shown in figure 7-9. Glass fiber- and graphite fiber-reinforced PMCs behave as shown in figure 7-9(b). By contrast, PMCs using fibers consisting of highly oriented long-chain polymers (e.g., Kevlar) collapse in a metal-like fashion using plastic deformation as the energy absorbing mechanism. The fragmentation/fracture mechanism typical of glass fiber PMCs can be very effective in absorbing energy, as illustrated in table 7-2.

It is particularly significant that although high-performance, highly oriented PMCs provide the maximum energy absorption, commercial-type PMCs yield specific energy numbers considerably superior to metals. Thornton and coworkers have accumulated extensive data on energy absorption in composites.[13] [14] [15]

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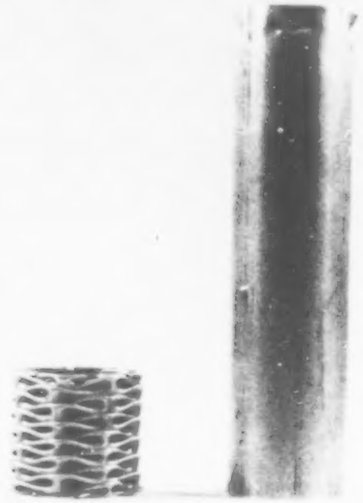
[13] P.H. Thornton and P.J. Edwards, *Journal of Composite Materials*, vol. 13, 1979, pp. 274-82.

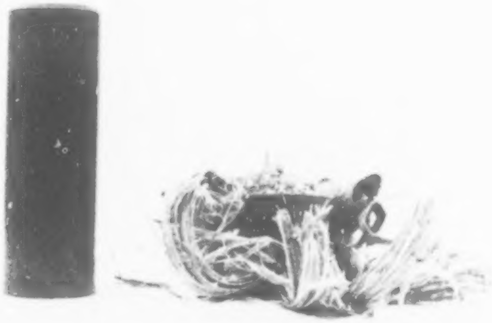
[14] P.H. Thornton and P.J. Edwards, *Journal of Composite Materials*, vol. 16, 1982, pp. 521-45.

[15] P.H. Thornton, J.J. Harwood, and P. Beardmore, International Journal of Composite Structures, 1985.

Figure 7-9.—Different Collapse Mechanisms in (a) Metal and (b) Composite Tubes, for Energy Absorption



a) energy. absorption by plastic deformation
b) fracture surface energy dissipation



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Virtually all the energy absorption data available to date have been developed for axial collapse of relatively simple structures, usually tubes. The ability to generate the same effective fracture mechanisms in complex structures is still unresolved. In addition, it is well known from observations on metal vehicles that bending collapse normally plays a significant part in the collapse of the vehicle structure, and it is consequently of considerable importance to evaluate energy absorption of composites in bending failure.

Just as in metals, little data are available on energy absorption characteristics in bending. There is no reason to believe that the energy absorption values of metals relative to PMCs in bending should change significantly from the ratios in axial collapse except that bending failure (fracture) in PMCs may tend to occur on a more localized basis than plastic bending in metals. If this does indeed occur, then the ratio could change in the favor of metals.

Other crash issues involve the capacity to absorb multiple and angular impacts and the long-term effects of environment on energy absorption capability. In general, practical data from a realistic, vehicle viewpoint are not yet in hand. An additional, significant factor is the consumer acceptance of these materials as perceived in relation to safety. A negative perception would be a serious issue on something as sensitive as safety, and better-than-steel crash behavior will be required before wide-scale implementation of PMCs can occur. Conversely, a positive perception would be a valuable marketing feature and provide an additional impetus for PMC applications.

Stiffness and Damping

Glass fiber-reinforced PMCs are inherently less stiff than steel. Some typical values for various types of PMC are listed in table 7-3. There are two offsetting factors to compensate for these material limitations. First, an increase in wall thickness can be used to offset partially the lesser material stiffness. Also, local areas can be thickened as required to optimize properties. Because PMCs have a density approximately one-third that of steel, a significant increase in thickness can be achieved while maintaining an appreciable weight reduction.

The second, and perhaps the major, offsetting factor is the additional stiffness attained in PMCs as a result of part integration. This integration leads directly to the elimination of joints, which results in significant increases in effective stiffness. It is becoming increasingly evident that this syn-

Table 7-3.—Typical Stiffness of Selected Composites

Material	Stiffness (10^6psi)
Unidirectional GrFRP	20
Unidirectional GlFRP	6
Unidirectional Kevlar	11
XMC	4.5
SMC-R50	2.3
SMC-25	1.3

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

ergism is such that structures of acceptable stiffness and considerably reduced weight are feasible in glass fiber-reinforced PMCs. As a rule of thumb, a glass FRP structure with significant part integration relative to the steel structure being replaced can be designed for a nominal stiffness level of 50 to 60 percent of the steel structure.[16] Such a design procedure should lead to adequate stiffness and to typical weight reductions of 20 to 50 percent.[17]

The stiffness requirement for vehicles is normally dictated by vehicle dynamics characteristics. The historical axiom in the vehicle engineer's design principles is the stiffer the better. However, there are some intangible factors that enter the overall picture, in particular the damping factor.

It is an oversimplification to assume stiffness alone dictates vehicle dynamics, although it unquestionably dominates certain categories. Damping effects can play an equally significant role in many categories of body dynamics, and the fact that the damping of PMC materials considerably exceeds that of metals is relevant to the overall scenario. Most experts involved with PMC component/structure prototype development feel that some aspect of body dynamics (usually noise or vibration) is improved but few quantitative data are available to document the degree of improvement. If customers share this perception, PMCs will receive impetus for structural usage.

POTENTIAL MANUFACTURING TECHNIQUES

The successful application of PMCs to automotive structures is more dependent on the ability to use rapid, economic fabrication processes than on any other single factor. The fabrication processes must also be capable of close control of PMC properties to achieve lightweight, efficient structures.

Currently, the only commercial process that comes close to satisfying these requirements is compression molding of sheet molding compounds (SMCs) or some variant on this process. There are, however, several developing processes that hold distinct promise for the future in that they have the potential to combine high rates of production, precise fiber control, and high degrees of part integration.

The requirements for precise fiber control, rapid production rates, and high complexity demand that automotive processes be in the region of developing processes shown schematically in figure 7-10. The three most important evolving processes are compression molding, high-speed resin transfer molding, and filament winding. Each of these processes is examined below.

Compression Molding

This section discusses compression molding techniques; these are most often used with thermosetting resins but can be used with thermoplastic resins.

Thermosetting Compression Molding

Figure 7-11 presents a schematic of the SMC process, depicting both the fabrication of the SMC material and the subsequent compression molding into a component. This technology has been widely used in the automobile industry for the fabrication of grille-opening panels on many auto lines, and for some exterior panels on selected vehicles. Tailgates (figure 7-12), and hoods (figure 7-13) are examples on autos and light trucks; the entire cab on some heavy trucks (figure 7-14) is constructed in this manner.

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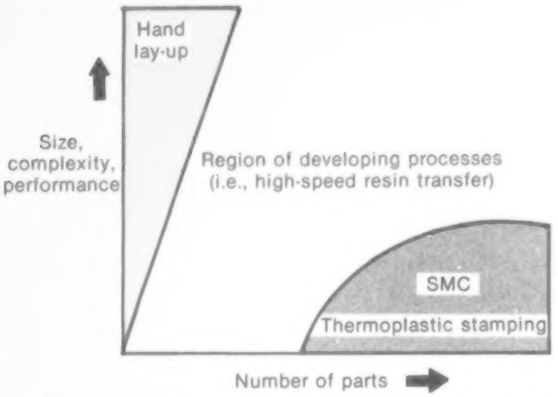
[16] Beardmore, Johnson, and Strosberg, op. cit., footnote 1.

[17] Ibid.

Figure 7-10.—Relationship Between Performance and Fabrication for Composites

Automotive Composite Process Development

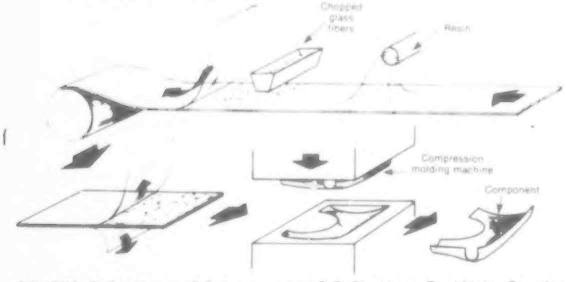


Viable commercial processes must be able to produce a large number of high performance parts.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-11.—Sheet Molding Compound Material Preparation and Component Fabrication

Sheet Molding

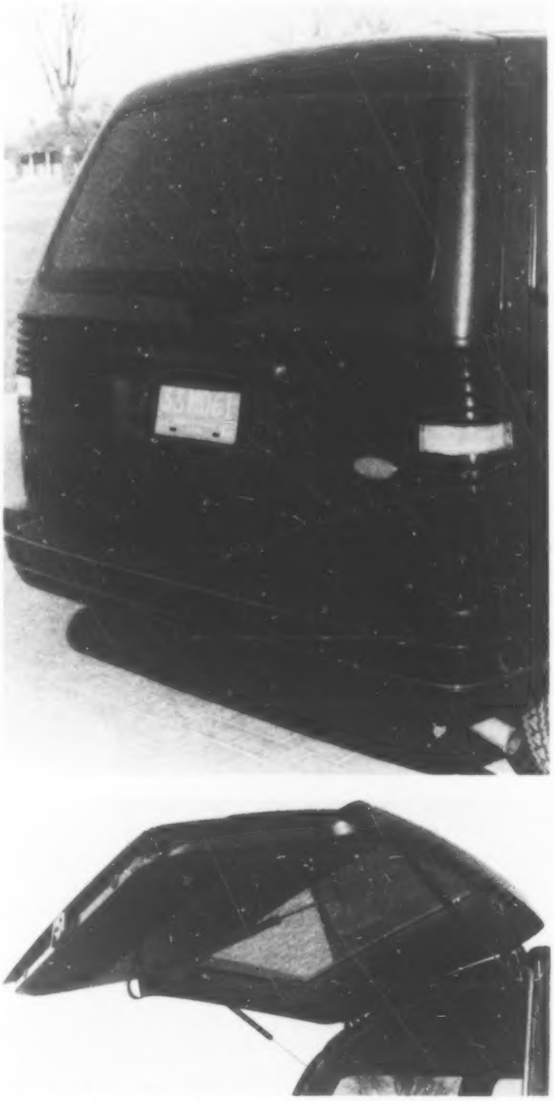


SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

The process consists of placing sheets of SMC (1 to 2 inch long chopped glass fibers in chemically thickened thermoset resin) into a heated mold (typically at 300° F) and closing the mold under pressures of 1,000 pounds per square inch (psi) for about 2 to 3 minutes to cure the material. Approximately 80 percent of the mold surface is covered by the SMC charge, and the material flows to fill the remaining mold cavity as the mold closes.

The above description of the SMC process delineates material primarily used for semistructural applications rather than high load bearing segments of the structure that must satisfy severe durability and energy absorption requirements.

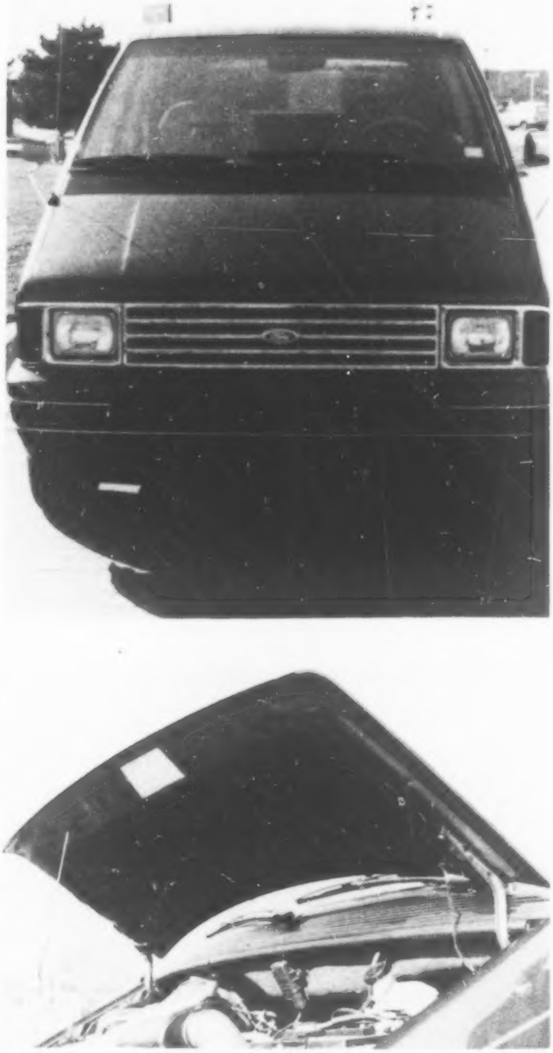
Figure 7-12.—Typical Sheet Molding Compound Production Aerostar Tailgate



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

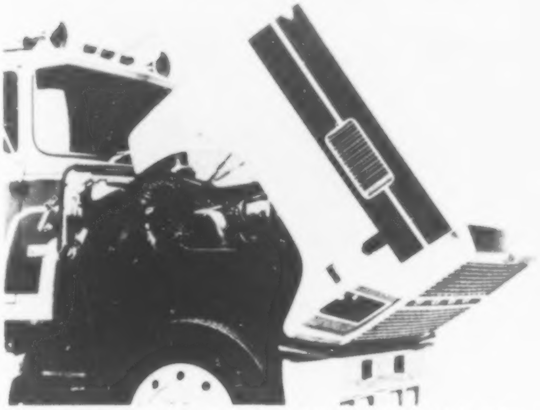
To sustain the more stringent structural demands, it is normally necessary to incorporate appreciable amounts of continuous fibers in predesignated locations and orientations.

Figure 7-13.—Typical SMC Production *Aerostar* Hood



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-14.—Typical SMC Truck Cab



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

The same basic SMC operation can be used to incorporate such material modifications either by formulating the material to include the continuous fibers along with the chopped fibers or by using separate charge patterns of two different types of material. The complexity of shape and degree of flow possible are governed by the amount and location of the continuous glass material. Careful charge pattern development is necessary for components of complex geometry. A typical example of a prototype rear floor pan fabricated by this technique is shown in figure 7-15.[18]

The limitations of compression molding of SMC-type materials in truly structural applications have yet to be established. Provided that continuous fiber is strategically incorporated, these materials promise to be capable of providing high structural integrity and may well prove to be the pioneering fabrication procedure in high load bearing applications. The state of commercialization of this process is advanced compared to other evolving techniques and this will provide a lead time for

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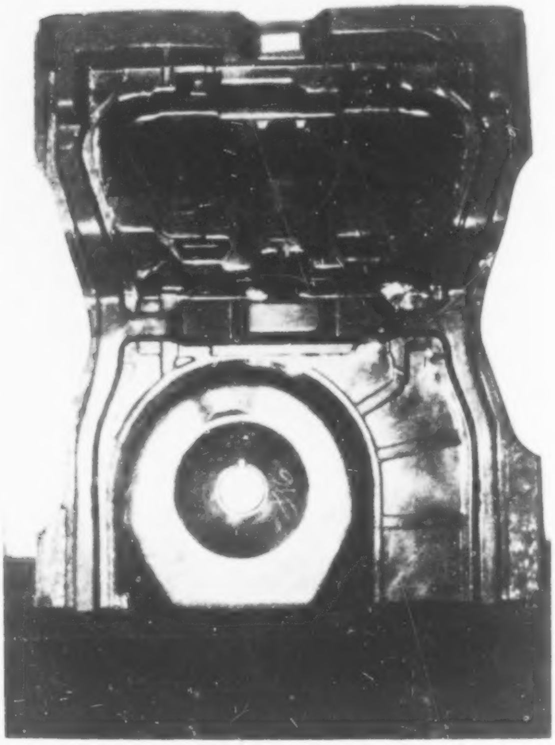
[18] C.F. Johnson and N.G. Chavka, "An Escort Rear Floor Pan," *Proceedings of the 40th Annual Technical Conference*, Atlanta, GA, Society of the Plastics Industry, January 1985.

Figure 7-15.—Prototype *Escort* Composite Rear Floor Pan



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987

compression molding to branch into higher performance parts.

Although compression molding of SMC-type materials is an economically viable, high production rate process in current use, there are some limitations inherent in the process. In the longer term, these will restrict applications and tend to favor the developing processes. For instance, material flow in the compression step results in imprecise control of fiber location and orientation. Typically, variations in mechanical properties of a factor of 2 throughout the component are not unusual based on an initial charge-pattern coverage of approximately 70 percent.

Such uncertainty in properties introduces reliability issues and encourages conservative designs that yield a heavier-than-necessary component or structure. Currently, extensive research efforts are underway to develop SMC-type materials that will allow 100 percent charge pattern coverage and that will attain high, uniform mechanical properties with minimal flow. These materials can also be molded at lower pressures on smaller capacity presses. Materials developments such as these may well make the newer breed of SMCs much more applicable to highly loaded structures than has hitherto been envisioned.

Another potential limitation of compression molding is the degree of part integration that is attainable. The basic strategy in PMC applications is to integrate as many individual (steel) pieces as possible to minimize fabrication and assembly costs (which offsets increased material costs) and to minimize joints (which increases effective stiffness). Compression molding requires fairly high molding pressures (about 1,000 pounds psi) and thus limits potential structures in area size and complexity (particularly in three-dimensional geometries requiring foam cores).

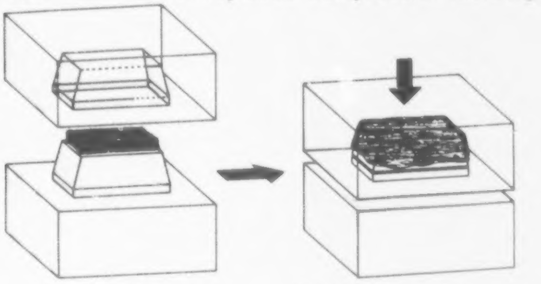
Consequently, although compression molding is likely to play a key role in the development of PMCs in structural automotive applications in the next decade, ultimately the process is unlikely to provide composite parts of optimum structural efficiency and weight. Nevertheless, compression molding is currently the only commercial PMC process capable of satisfying the economic constraints of a mass-production industry.

Thermoplastic Compression Molding

The process of thermoplastic compression molding (stamping) is attractive to the automotive industry because of the rapid cycle time and the potential use of some existing metal stamping equipment. Thermoplastic compression molding at its current level of development achieves cycle times of 1 minute for large components.

Figure 7-16 presents a schematic of the process. Typically, a sheet of premanufactured thermoplastic and reinforcement is preheated above the melting point of the matrix material and then rapidly transferred to the mold. The mold is quickly closed until the point where the material is contacted, and then the closing rate is

Figure 7-16.—Thermoplastic Compression Molding



Heated blank loaded into mold

Mold closing, compressing material to fill cavity

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

slowed. The material is formed to shape and flows to fill the mold cavity much the same as thermoset compression-molded SMC. The material is cooled in the mold for a short period of time to allow the part to harden, and then the mold is opened and the component is removed.

Thermoplastic compression molding is currently used in automobiles to form low-cost semistructural components such as bumper backup beams, seats, and load floors. Commercially available materials range from wood-filled polypropylene and short glass-filled polypropylene with relatively low physical properties, to continuous random glass-reinforced materials based on polypropylene or PET which offer somewhat higher physical properties. Other materials, based on highly oriented reinforcements and such resins as polyetheretherketone (PEEK) and polyphenylene sulfide (PPS), are in use in the aerospace industry. These materials are expensive and are limited in their conformability to complex shapes.

Higher levels of strength and stiffness must be developed in low-cost materials before they can be used in structural automotive applications. Attempts have been made to improve the properties of stampable materials through the use of separate, preimpregnated, unidirectional reinforcement tapes. These materials are added to the heated material charge at critical locations to improve the local strength and stiffness. Using these materials adds to the cost of the material and increases cycle times slightly.

Although effective for simple configurations, location of the oriented reinforcement and reproducibility of location are problems in complex parts. To be most effective, these types of reinforcements ultimately will have to be part of the premanufactured sheet or be robotically applied. Current research is in progress in the area of thermoplastic sheet materials with oriented reinforcement in critical areas. For application to automotive structures, these materials will have to retain the geometric flexibility in molding (i.e., ability to form complex shapes with the reinforcement in the correct location) exhibited by today's commercial materials.

The question of part integration is a major issue in the expanded use of this process. The high pressures (1,000 to 3,000 psi) required limit the size of components that can be manufactured on conventional presses. Thermoplastic compression molding is also limited in its ability to incorporate complex three-dimensional cores required for optimum part integration.

If very large integrated structures are required from an overall economic viewpoint, thermoplastic compression molding will be restricted to smaller components such as door, hood, and deck lid inner panels in which geometry is relatively simple and/or part integration is limited due to physical part constraints. If very large-scale integration proves too expensive, then thermoplastic compression molding will exhibit increased market penetration. Ongoing long-range research in the area of low-pressure systems and incorporation of foam cores in moldings could significantly alter this outlook in the longer term.

High-Speed Resin Transfer Molding

Fabrication processes that permit precise fiber control with rapid processability would overcome many of the deficiencies outlined above. The use of some kind of preform of oriented glass fibers preplaced in the mold cavity, followed by the introduction of a resin with no resultant fiber movement would satisfy the requirements for optimum performance and high reliability.

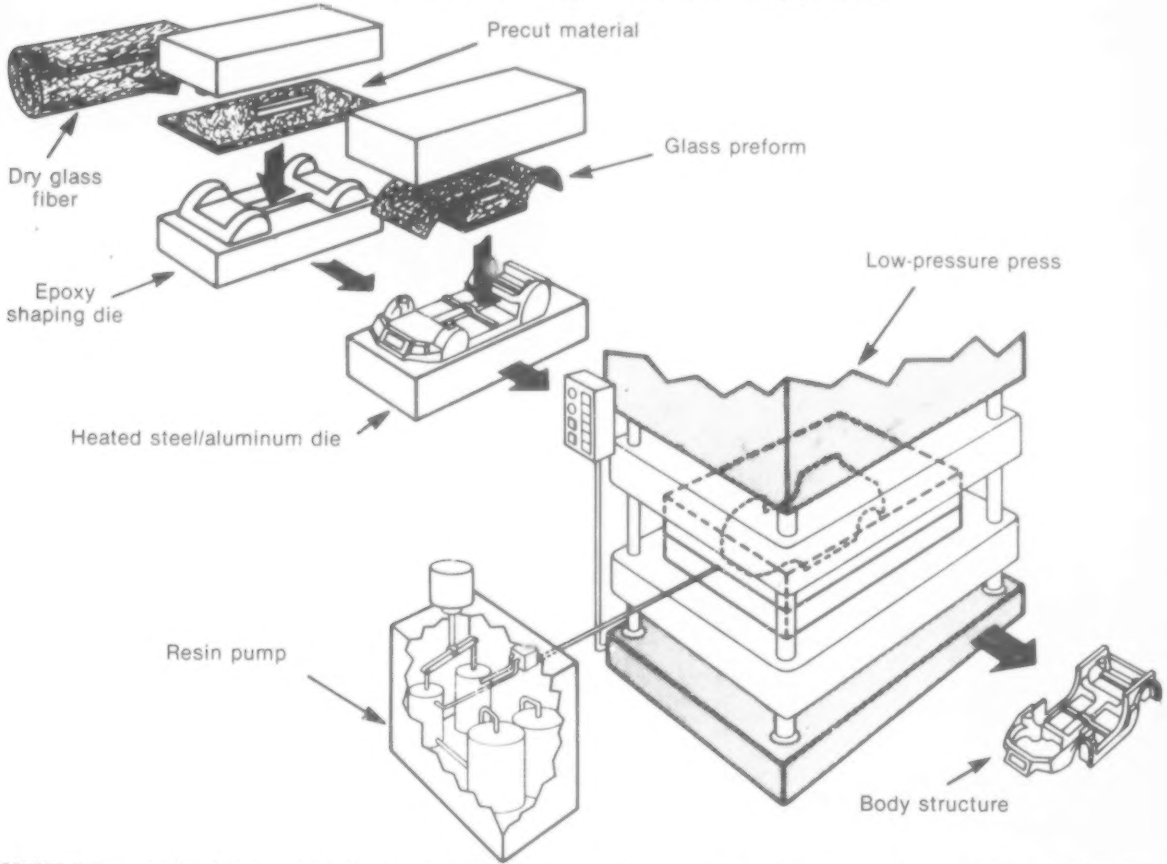
The basic concepts required for this process are practiced fairly widely today in the boat-building and specialty-auto business. However, with few exceptions, the glass preform is hand-constructed and the resin injection and cure times are of the order of tens of minutes or greater. Also, dimensional consistency necessary for assembling high-quality products has not been studied for this process.

Major reductions in manufacturing time and automation of all phases of the process are necessary to increase automotive production rates. However, the basic ingredients of precise fiber control and highly integrated complex part geometries (including, for instance, box sections) are an integral part of this process and offer potentially large cost benefits.

There are two basic elements associated with the high-speed resin transfer molding (HSRTM) process that must be developed. The assemblage of the glass preform must be developed such that it can be placed in the mold as a single piece. In addition, the introduction of the resin into the mold must be rapid and the cure cycle must be equally fast to provide a mold-closed/mold-open cycle time of only a few minutes. A schematic of the process is presented in figure 7-17.

There are two processes currently in use that may have the potential to offer rapid resin injection and cure times. One is resin transfer molding. Currently in widespread use at slow rates,

Figure 7-17.—High-Speed Resin Transfer Molding (HSRTM)



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

it could be accelerated dramatically by the use of low-viscosity resins, multiport injection sites, computer-controlled feedback injection controls, and sophisticated heated steel tools. There do not appear to be any significant technological barriers to these kinds of developments, but it will require a strong financial commitment to prove out such a system. A schematic of the process is presented in figure 7-18, which also illustrates a variant on the process usually termed squeeze molding.

The second process that promises rapid injection and cure cycles is reaction injection molding (RIM). In reaction injection molding, two chemicals are mixed and injected simultaneously; during injection the chemicals react to form a thermosetting resin. Once the dry glass preform is in the mold, the resin can be introduced by any appropriate procedure, and reaction injection would be ideal, provided the resultant resin has adequate mechanical properties. The inherent low viscosity of RIM resins would be ideal for rapid introduction into the mold.

Full three-dimensional geometries including box sections, are attainable by preform molding. In addition, only low-pressure presses are necessary. The high degree of part integration maximizes effective stiffness and minimizes assembly.

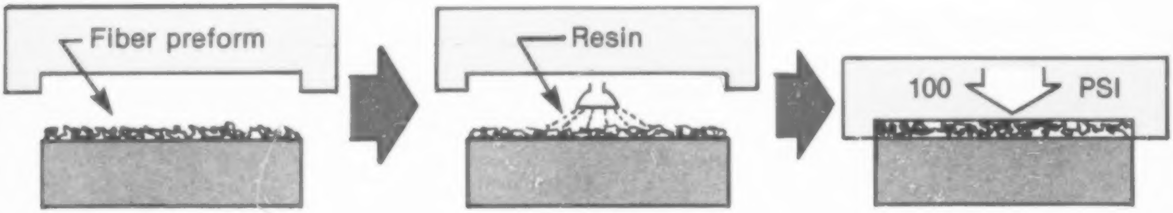
In principle, major portions of vehicles could be molded in one piece; for instance, Lotus auto body structures consist of two major pieces (albeit molded very slowly) with one circumferential bond. If similar-size complex pieces could be molded in minutes, a viable volume production technique could result.

Filament Winding

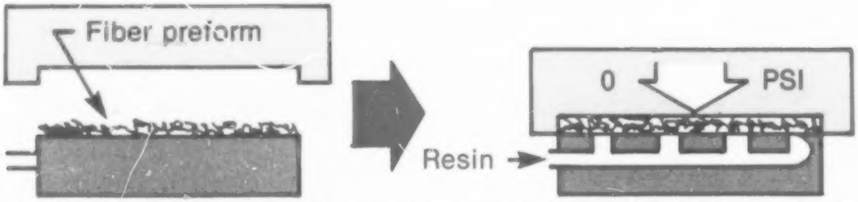
Filament winding is a PMC fabrication process that for some geometric shapes can bridge the gap between slow, labor-intensive aerospace fabrication techniques and the rapid, automated fabrication processes needed for automotive manufacturing. The basic process uses a continuous fiber reinforcement to form a shape by winding over some predetermined path. Figure 7-19 provides a process schematic.

Figure 7-18.—Squeeze Molding and Resin Transfer Molding

Squeeze molding

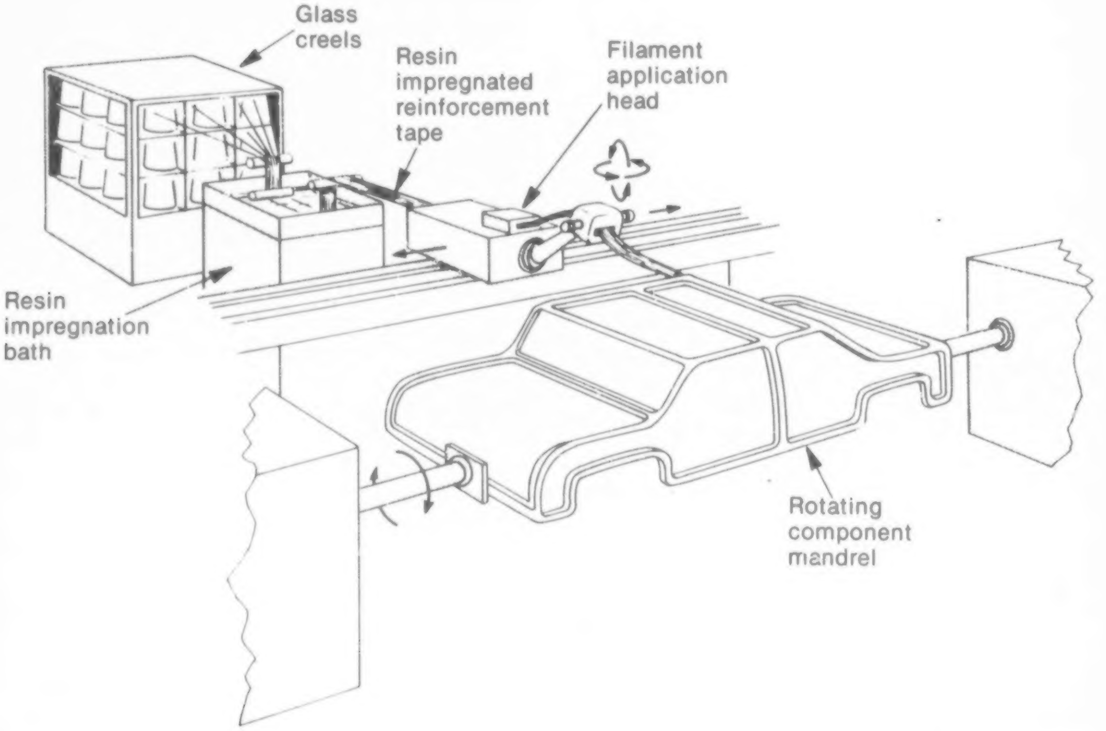


Resin transfer molding



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-19.—Filament Winding Process


Glass creels
Resin impregnated reinforcement tape
Filament application head
Resin impregnation bath
Rotating component mandrel

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

The complexity and accuracy of the winding path are highly controllable with microcomputer-controlled winding machines. Thin, hollow shapes having high fiber-to-resin ratios are possible, thereby making the process well suited to lightweight, high-performance components. Glass fiber, aramid, or carbon fiber can be used as the winding material. Filament winding can use either thermosetting or thermoplastic resin systems.

The uniform fiber alignment afforded by the process provides high reliability and repeatability in filament-wound components. Some simple shapes, such as leaf springs, can be fabricated by this process and are currently in production on a limited basis.

Thermoset Filament Winding

The majority of filament winding done today uses thermosetting resin systems. In the thermoset filament-winding process, the resin and reinforcement fibers are combined (referred to as wetting out of the reinforcement) immediately prior to the winding of the fibers onto the part. The wetting-out and winding processes require precise control of several variables. Reinforcement tension, resin properties, and the fiber/resin ratio all relate directly to the final physical properties of the part. As the winding speed and part complexity increase, these variables become increasingly difficult to control.

Winding of complex parts at automotive production rates will require major process developments. The likely potential of thermoset filament winding in automotive applications is in the fabrication of simple shapes such as leaf springs, in which the cost penalty involved due to slow production speeds can be offset by a need for high reliability and maximum use of material properties.

Thermoplastic Filament Winding

Filament winding of thermoplastic materials represents both the leading edge of this technology and the area in which its potential benefit to the automotive industry is greatest.

Thermoplastic filament winding uses a reinforcement preimpregnated with a thermoplastic resin rather than a reinforcement impregnated with a thermosetting resin at the time of winding. The preimpregnated filament or, more often, tape, is wound into the appropriate shape in a manner similar to the thermosetting filament-winding process, with the exception of a local heating and compaction step.

The reinforcement tape is heated with hot air or laser energy as it first touches the mandrel. The heat melts the thermoplastic matrix both on the tape and locally on the substrate permitting a slight pressure applied by a following roller to consolidate the material in the heated area. Because the reinforcement filament is already wet out in a prepregging process, the substrate is solidified over its entirety with the exception of a small zone of molten material in the area of consolidation.

The limitations with respect to filament tension, filament wet-out, and speed at which a wet filament can be pulled through a payout eye are no longer a major concern with thermoplastic filament winding. Thick sections can be rapidly wound, and nongeodesic and concave sections can be formed. However, the applicability to geometries as complex as body structures is not established. Currently, problem areas exist in the carryover of physical properties due to the limited amount of research that has been done on the process. There are problems with the control of the heating and consolidation of the thermoplastic materials that yield less than predicted values for tensile strength and interlaminar shear strength.

Although the thermoplastic materials will likely expand the structural component applications in which thermoplastic filament winding can economically compete with thermoset filament winding, the increased speed and shape capabilities will not entirely offset the limited degree of part integration possible. The inability to integrate box sections with large flat panels in a one-piece structure having complex geometry will tend to limit the penetration of filament winding in body structures.

IMPACT ON PRODUCTION METHODS

The following sections discuss the various impacts of these candidate technologies on automobile production methods.

Manufacturing Approach

The manufacturing approach for producing autos with PMC structural parts will be considerably different from the methods employed for building conventional vehicles with steel bodies. Currently, many domestic automotive assembly plants for steel vehicles are used for very little basic manufacturing. Instead, high-volume sheet steel stamping plants, geographically located to service several assembly plants, produce body components and small assemblies and ship them to the assembly plants. The plants assemble the sheet metal components into an auto body structure as presented in table 7-4 and figure 7-20a and b.

An auto body is a complex structure, and its design is influenced by many demanding factors. At the present time, it appears that two systems can be considered as possible processes to build the structural panels for PMC auto bodies.

One system consists of compression molding. Compression molded thin-walled panels are first bonded together to form structural panels (see figure 7-21) and then the structural panels, are assembled to form auto bodies. The other system involves HSRTM, in which preforms of fiber reinforcement are combined with foam cores, placed in a mold, and resin-injected to form large, three-dimensional structural panels (see figure 7-22). These panels are then assembled into auto bodies. It is important to note that the filament-winding process is viewed as a limited construction method largely due to the restricted complexity that is available with this technique.

Table 7-4.—Typical Body Construction System: Steel Panels

- Build front structure—assemble aprons, radiator support, torque boxes, etc. to dash panel
- Build front floor pan assembly
- Assemble front and rear floor pan into underbody assembly
- Complete spot welding of underbody assembly
- Transfer underbody to skid
- Build left-hand and right-hand bodyside assemblies
- Move underbody, bodyside assemblies, cowl top, windshield header, rear header, etc. into body buck line and tack-weld parts
- Complete spot welding of body
- Braze and fusion-weld sheet metal where required
- Assemble, tack-weld and respot roof panel to body
- Assemble front fenders to body
- Assemble closure panels (doors, hood, decklid) to body
- Finish exterior surface where required

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Therefore, it cannot now be considered as a competitive process for high-volume body structure fabrication.

Compression Molded Structural Bodies

Compression molded structural panels might be produced as presented in table 7-5 and figure 7-21. Panel assemblies (side panels, floor pans, roof panels, etc.) are produced from inner and outer components. First, SMC sheet must be manufactured and blanks of proper size and weight arranged in a large predetermined pattern on the die surface. The panels are then molded in high-tonnage presses. After molding, the parts are processed in a number of secondary operations, bonded together, and transported to the body assembly line.

Body construction commences with the floor panel being placed in an assembly fixture. Side panel assemblies and mating components are bonded in place. Attachment points for the exterior body panels are drilled and the body structure is painted prior to transporting to the trim operations. (The body construction sequence is described later, see table 7-9 and figure 7-24.)

High-Speed Resin Transfer Molded Structural Bodies

HSRTM processing consists of three stages that involve making a dry glass fiber preform, combining the preform with foam cores, and injecting resin into the mold to infiltrate the preform.

First, dry glass preform reinforcements must be fabricated. The preform may be composed of primarily randomly oriented glass fibers with added directional glass fibers or woven glass cloth for

Figure 7-20(a).—Typical Assembly of Steel Underbody

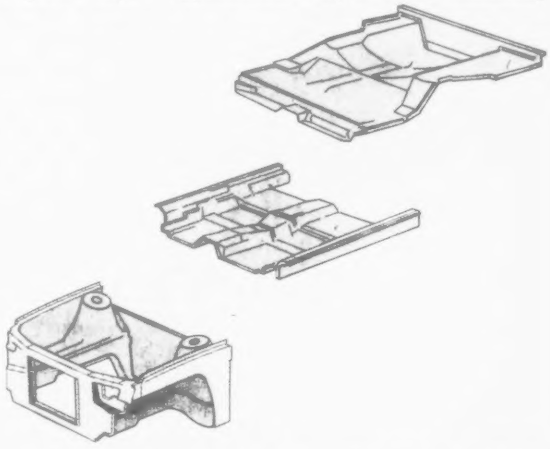
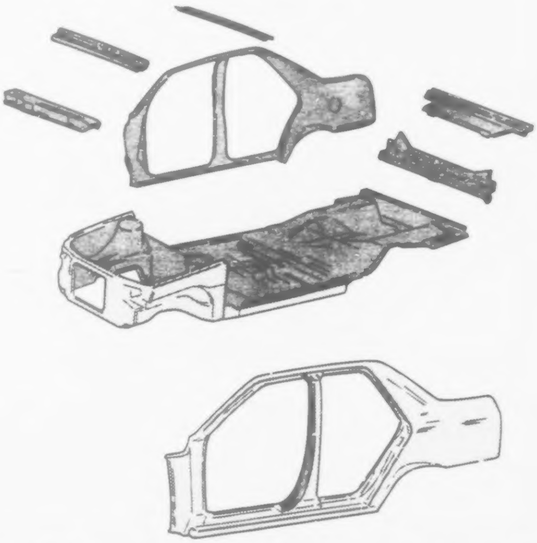
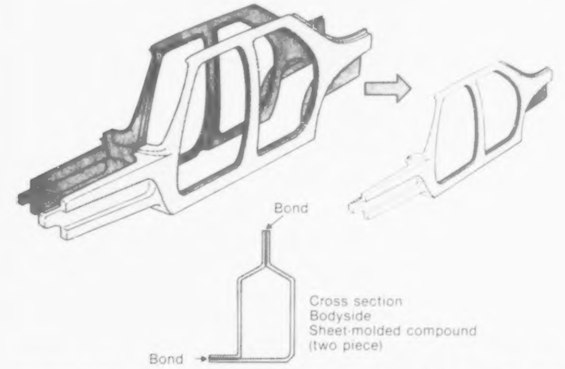


Figure 7-20(b).—Typical Assembly of Underbody, Bodyside Assemblies, Etc. into the Completed Steel Body Shell



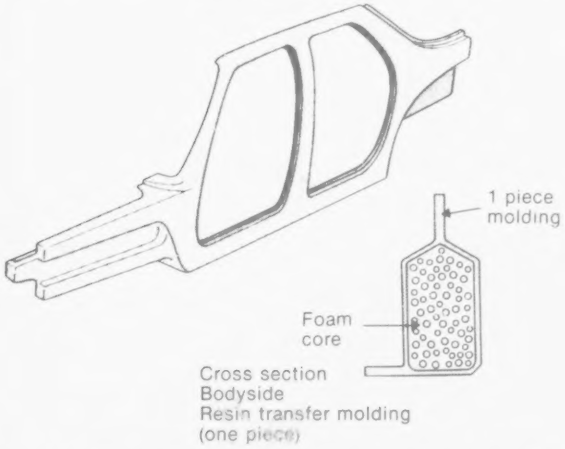
SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-21.—Typical Assembly of Composite Bodyside Panel by Adhesive Bonding of Inner and Outer SMC Molded Panels



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Figure 7-22.—Typical One-Piece Composite Bodyside Panel With Foam Core Molded by High-Speed Resin Transfer Molding



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7-5.—Compression Molded Structural Panels

- Fabricate and prepare SMC charge
- Load charge into die and mold panel
- Remove components from molding machine (inner and outer panels), trim and drill parts as required
- Attach reinforcements, latches, etc., to inner and outer panels, with adhesive/rivets
- Apply mixed, two component adhesive to outer panel
- Assemble inner and outer panels, clamp and cure
- Remove excess adhesive
- Remove body panel from fixture and transport to body construction line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7-6.—Preform Fabrication Sequence

- Apply random glass fibers over mandrel
- Apply directional fibers (or woven cloth) for local reinforcement
- Stabilize preform
- Remove preform and transfer to trim station
- Trim excess fibers
- Transfer to HSRTM panel molding line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

local reinforcement of high-stress areas. To be economically viable, preform fabrication must be accomplished by a highly automated technique. The process sequence is described in table 7-6.

Second, foam core reinforcements must be fabricated to obtain three-dimensional inserts, such as those used in rockers and pillars. Local metal reinforcements and fasteners can be prepositioned in the mold at this point during foam fabrication. The chemicals are subsequently introduced into the mold and the resulting reaction yields an accurately shaped foam part. The process sequence is described in table 7-7.

Third, the body structural panel is molded. A gel coat may be sprayed in both the lower and upper mold cavities to obtain a smoother surface on the finished part. Preforms, foam cores, and any necessary additional local reinforcements and fasteners are placed in the respective lower and upper mold cavities. In high production,

Table 7-7.—Foam Core Fabrication Sequence

- Clean mold and apply part release
- Install reinforcements and basic fasteners
- Close mold
- Mix resins and inject into mold
- Chemicals react to form part
- Open mold
- Unload part and place on trim fixture
- Trim and drill excess material
- Transport to HSRTM body panel line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

these operations must be carried out robotically. The mold is closed and a vacuum may be applied. The resin is injected, infiltrates the preform, and cures to form the body structural panel. The molding is then removed from the die and trimmed. This process sequence is described in table 7-8 and illustrated in figure 7-22.

The final stage of body construction is the assembly of the individual panels. The underbody panel is placed on the body construction line. Adhesive is applied to the side panels by robots in the appropriate joint locations, the side panels are mated to the underbody and clamped in place, and the fasteners are added. Similarly, the remainder of the body structure is located and bonded to form a complete auto body. After curing, the body is washed and dried, prior to transfer to trim operations. This process sequence is described in table 7-9 and illustrated in figure 7-23.

(Note that the body assembly sequence given in table 7-9 is essentially common to both compression molding and HSRTM. This is only one illustration of the assembly of a number of moldings to form the body—the number of moldings could vary from 2 to 10 depending on the specific design and manufacturing details.[19])

Table 7-8.—HSRTM Molded Structural Panels

- Clean mold and apply part release
- Spray gel coat into mold (optional)
- Insert lower preforms and local woven fiber reinforcements
- Insert specialized reinforcements and fasteners
- Insert foam cores
- Insert upper preforms and local woven fiber reinforcements
- Close mold
- Apply vacuum to mold (optional)
- Inject resin and allow chemicals to react
- Open mold
- Remove assembly and place in trim fixture
- Trim and drill body panel
- Transport to body assembly line

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7-9.—Body Construction Assembly Sequence

- Place underbody in body build line
- Apply adhesive to bond lines of side panels and cowl
- Mate side panels to underbody, clamp and insert fasteners
- Apply adhesive to cowl top assembly, lower back panel and mate
- Apply adhesive to roof panel and mate to body side panels
- Transfer body to final trim operations
- After final trim, the painted exterior body panels are assembled to the auto body

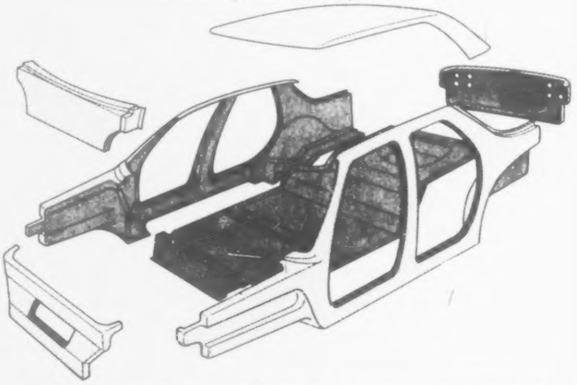
SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987

As noted, figure 7-23 is a schematic of a multipiece PMC body. For comparison, a two-piece HSRTM body construction is illustrated in figure 7-24 to indicate the various levels of part integration that might be achieved using PMCs. In both these scenarios, the body shell would consist of PMC structure with no metal parts except for molded-in steel reinforcements.

Assembly Operation Impact

In both the compression molding and HSRTM scenarios, there would be a considerable change

Figure 7-23.—Typical Body Construction Assembly for Composite Body Shell



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

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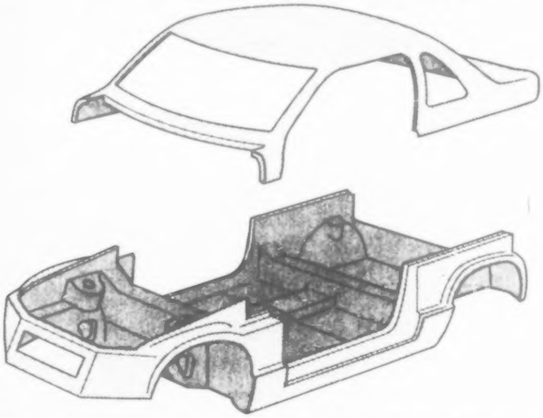
[19] Beardmore, Johnson, and Strosberg, op. cit., footnote 1.

Figure 7-24.—Typical Body Construction Assembly Using Two Major Composite Moldings



SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

Table 7-10.—Effect of Composites on Body Complexity

Vehicle design and material	Typical number of major parts in body structure	Typical number of assembly robots
A. Conventional welded steel body structure	250 to 350	300
B. Molded SMC body structure	10 to 30	100
C. High-speed resin transfer molded composite/body structure	2 to 10	50
Estimated part reduction (A less B)	240 to 320	200 to 250
Estimated part reduction (A less C)	248 to 340	250 to 280

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

in the assembly operations for PMC vehicles versus conventional steel vehicles. The number of component parts in a typical body structure (body-in-white less hoods, doors, and decklids) varies with vehicle design and material, as presented in table 7-10.

The dramatic reduction in the number of parts to be assembled in a PMC vehicle would result in a corresponding reduction in the number of subassembly operations and amount of subassembly equipment, as well as a reduction in the required floorspace. For instance, robots used to produce PMC assemblies can lay down an adhesive bead considerably faster than robots can spotweld a comparable distance on mating components. Therefore, it is anticipated that there would be a considerable reduction in the number of robots and complex welding fixtures required.

Labor Impact

The design and engineering skills that would be required to apply PMCs would be somewhat different from the skills used for current metal applications. A broader materials training curriculum would be required because the chemical, physical, and mechanical properties of PMCs differ significantly from those of metals. These programs are currently being developed at some universities but significant expansion would be necessary to ensure this trend on a broader scale.

The overall labor content for producing a PMC body would similarly be reduced as numerous operations would be eliminated. However, it is important to note that body assembly is not a labor-intensive segment of total assembly. Other assembly operations that are more labor-intensive (e.g., trim) would not be significantly affected. Thus, the overall labor decrease due to PMCs might be relatively small.

The level of skills involved in PMC assembly line operations (e.g., bonding operations) is not expected to be any more demanding than the skill level currently required for spotwelding conventional body assemblies. In either case, good product design practice dictates that product assembly skill requirements be matched with the skill levels of the available workers to obtain a consistently high-quality level.

IMPACT ON SUPPORT INDUSTRIES

The increased use of polymer composites could strongly affect the existing automotive support industries as well as promote the development of new ones.

Material Suppliers, Molders, and Fabricators

PMC vehicle body structures of the future, whether built with compression-molded or HSRTM parts, are expected to be designed with components integrated into modular subassemblies. Therefore, these units will be of considerable size and are not conducive to long-range shipping. Manufacturing on site in a dedicated plant for molding body construction and assembly operations, just prior to trim and final assembly of the vehicle, will become necessary.

PMC automobile production, in relatively high volumes, will require additional qualified supplier capacity. The extent of these requirements will be dependent on the economic attractiveness and incentives for developing in-house capacity by the automotive manufacturers. Fortunately, these demands are likely to be evolutionary, in that the automotive industry would undoubtedly commence with low annual volume (10,000 to 60,000) PMC body production units.[20] When (and if) higher volume production of PMC bodies is planned, additional supplier capacity can be put in place as a result of supplier/manufacturer cooperation throughout the normal lead time (4 to 6 years) for the planning, design, and release of a new vehicle to manufacturing.[21]

Although compression molding is the most mature of the evolving PMC production techniques, a major conversion to SMC for body structures would require a substantial increase in resin and reinforcement output, mold-building capacity, molding machine construction, component molding, subassembly facilities, adhesives, and quality control tools, etc.

If the HSRTM processing concept is used, resin and reinforcement suppliers would need to substantially expand their output (as in the case of compression molding) and perhaps develop new products to meet the unique demands of the process. Tooling is similar in construction to that used in injection molding, and therefore manufacturers of this type of tooling would likely expand to fill the need. If inexpensive electroformed molds, which consist of 0.25 inch of electroplated nickel facing on a filled epoxy backing (used today for low-pressure or vacuum-assisted molding) become feasible, this phase of the industry would have to be developed and expanded. Because molding pressures for this process are low, high-tonnage hydraulic presses would not be needed. However, companies specializing in automation and resin handling equipment would play an increased role.

If PMC structures were suddenly implemented, there would be an expected shortfall of qualified molders and fabricators regardless of the process chosen. It is more likely, however, that implementation would be evolutionary, and the supply base would be addressed during the PMC vehicle planning and design stage. To enlarge the supply base, the auto industry is currently working with, and encouraging, qualified vendors to expand and/or diversify, as required, to support product plans. Additionally, with growth in PMC demand, new suppliers would be expected to become qualified.

Current suppliers may also form joint ventures and/or make acquisitions to expand capabilities during the phase-in period of PMC structures. Along with the need to expand materials supply and facilities, there is the significant need to develop and retrain qualified personnel to provide support for both supplier and automotive industry operations.

The current molding capacity for SMC devoted to the automotive industry is of the order of 500 million to 750 million pounds annually.[22] Figure 7-25 projects the additional volume of PMCs that would be needed as a function of producing a high volume of autos with a high content of composites. The data are based on a substitution for

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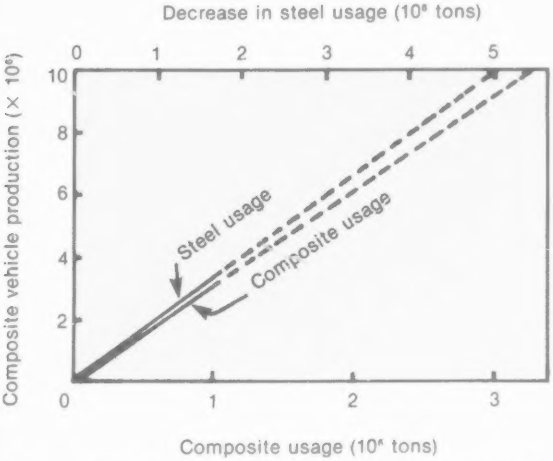
[20] Ibid.

[21] Ibid.

[22] Ibid.

Figure 7-25.—Effect of Composite Use on Steel Use in Automobiles



Increase in composites usage and associated decrease in steel usage for various production volumes of composite-intensive vehicles. Assumes 1,000 lb. of steel is replaced by 650 lb. of composites in a typical vehicle weighing 2,700 lb. that contains 1,600 lb. of steel.

Two million composite-intensive vehicles per year causes a loss of one million tons of steel, which is roughly 12 percent of steel usage in automobiles, see table 7-11.

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

a typical vehicle weighing 2,700 pounds and containing 1,600 pounds of steel. Of this 1,600 pounds of steel, 1,000 pounds of steel have been replaced by 650 pounds of PMCs. It is evident that there would be a relatively massive incremental amount of PMCs needed for even 1 million vehicles per year—about 300,000 tons (650 million pounds); i.e., roughly a doubling of current SMC capacity.[23] Each additional million vehicles would require the same increase, creating (ultimately) an enormous new industry.

Steel Industry

The implementation of PMCs in automobiles would clearly have an impact on the steel industry. As with the plastics industry, this impact would be volume-dependent. In the initial stages, with volumes in the range of 10,000 to 60,000 vehicles per year, there would be only a minimal effect—a small loss in steel tonnage, some excess press capacity, and some additional stamping die building capacity.[24] The loss of steel tonnage from the steel mills would cause additional problems for this already beleaguered segment of industry. Both captive and/or supplier stamping plants would have idle capacity. Stamping die builders would lose orders, unless they could also build molds for plastics. However, these potential problems for the steel industry would be evolutionary and would take several years to occur after the successful introduction of vehicles using this technology.

Figure 7-25 can be used to place this potential impact in perspective. The decrease in steel use as a function of increasing production volume of cars with a high PMC content would become significant only at intermediate volume levels. The data reproduced in table 7-11 show that at volumes of up to 500,000 PMC vehicles per year, automotive use of steel would drop only about 250,000 tons (or 3 percent) per year.[25] Since motor vehicle manufacturing uses about 15 percent of all steel consumption in the U.S.,[26] steel consumption would drop 0.45 percent for volumes of 500,000 PMC vehicles per year. Major steel production decreases would result only from a major change in PMC vehicle volume—e.g., 2 million vehicles or more.[27]

Table 7-11.—Automotive Steel Usage (based on annual volume of 10^7 vehicles)

Production volume of composite-intensive vehicles	Steel usage (10^6) tons
0	8
50,000	7.975
500,000	7.75
5,000,000	5.5
10,000,000	3.0

SOURCE: P. Beardmore, C.F. Johnson, and G.G. Strosberg, Ford Motor Co., "Impact of New Materials on Basic Manufacturing Industries, A Case Study: Composite Automobile Structure," contractor report for OTA, 1987.

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[23] Ibid.

[24] Ibid.

[25] If a vehicle is specifically designed for PMCs instead of steel, and, for instance, the volume is on the order of 500,000 units, the impact would be greater.

[26] U.S. Department of Commerce, Bureau of Economic Analysis, *The Detailed Input-Output Structure of the U.S. Economy, 1977*, vol. 1, Washington, DC, 1984.

[27] Beardmore, Johnson, and Strosberg, op. cit.

It is also recognized that the steel industry and its suppliers are aggressively seeking methods to reduce costs and provide a wider range of steels. This healthy economic competition between steel and PMCs will have an effect on the timing of PMC auto introductions and the volumes to be produced. World competition in the steel industry is leading to the availability of a wider range of high-strength steels with improved quality, resulting in an increase in productivity for the end user. The balance between improved economic factors for steel use and the rate of improvement of PMCs processing will dictate the use, rate of growth, and timing of the introduction of PMC vehicles.

Repair Service Requirements

Another support industry of importance is the PMC repair service required to repair vehicle damage caused in accidents, etc. During the design process, automobile engineers will design components and body parts to simplify field repairs. For repair of major damage, large replacement components or modules will have to be supplied. At the present time, the comparative expense of repairing PMC structures relative to steel is unclear. Replacement parts or sections will tend to be more expensive. However, low-energy collisions are expected to result in less damage to the vehicle. Thus, the overall repair costs across a broad spectrum of vehicles and damage levels are not anticipated to be any higher than current levels.

Exterior SMC body panel repair procedures are already in existence at automotive dealerships and independent repair shops specializing in fiberglass repairs. With additional PMC use, it is expected that the number of these repair service facilities will increase. To repair the PMC structure, dealers and independent repair centers will need new repair procedures and repair materials. The development of the appropriate repair procedures will be contained well within the time frame of PMC vehicle introduction. There will be new business opportunities to establish additional independent shops.

As with any new vehicle design, PMC repair procedures must be fully developed and standardized, along with the additional training of repair personnel. This training will require skill levels equivalent to those required for steel repair.

PMC Vehicle/Component Recycling

The recycling industry is another support industry that will undergo significant change in the longer term if PMC vehicles become a significant portion of the volume of scrapped vehicles. Current steel vehicle recycling techniques (shredders and magnetic separators) will not be applicable, and cost-effective recycling methods will need to be developed exclusively for PMCs. Low volumes of scrap PMC vehicles will have minimal effect, but the problems will increase as the volume reaches a significant level. This level is estimated to be in the range of 20 percent or more of the total vehicles to be salvaged.[28]

Plastics must be segregated into types prior to recycling. Currently, only clean, unreinforced thermoplastic materials can readily be reclaimed, but the techniques are somewhat inadequate and tend to be very expensive. Fortunately, the calorific value of many thermoplastics approaches that of fuel oil. Some waste-incinerating plants now operate with various types of plastics as fuel. One developing use for plastic waste involves pulverizing plastics and using their calorific value as a partial substitute for fuel oil in cement kilns. Some plastics in automobiles can be recycled by melt recovery, pyrolysis, and hydrolysis, but cost-effective methods are not yet in place.

Thermoset plastic components, such as SMC panels and other PMC body components, currently cannot easily be reclaimed because of their relatively infusible state and low resin content. Grinding, followed by reuse in less demanding applications such as roadfill or building materials, is possible, but is not currently economical. Consequently, these kinds of parts are used as landfill or are incinerated. Again, at low volumes, these recycling procedures are acceptable, but they would not be viable at high scrap rates.

Without the advent of some unforeseen recycling procedures, it appears likely that incineration will have to be the major process for the future. The viability of incineration will either have to be improved by more efficient techniques for more favorable economics or some penalty will likely have to be absorbed by the product.

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[28] Ibid.

POTENTIAL EFFECTS OF GOVERNMENTAL REGULATIONS

Any major potential changes in automotive industrial practice, such as the large-scale substitution of a new structural material, must take into consideration not only current regulations but also future regulations that may already be under consideration or that may be initiated *because* of the potential changes in industrial practice. One example is the increased safety (crash-resistance) requirements already under active consideration. Another is the potential increases in CAFE standards for the 1990s. Although the following discussion of such potential regulations is not comprehensive, it serves to illustrate the importance of such considerations in introducing major materials changes to the automotive industry.

Health Safeguards

The introduction of fiber-reinforced plastics in significant volumes into the automotive workplace may raise health and environment concerns. Any fibers in very fine form have the potential to create lung and skin problems, and although glass fibers may be among the more inert types of fiber, there must still be adequate precautions taken in handling these fibers.

Currently, glass fibers are widely used in various industries such as molding industries, boat building, and home construction; extension to the automotive industry would probably not require development of safeguards other than those used within those existing industries.

However, the widespread nature of the automotive business would undoubtedly raise awareness of potential health risks and could precipitate more stringent requirements for the workplace. Although such additional precautions may not pose a technological problem, the extent of the regulations could have a significant effect on the economic viability of the use of composites.

Similarly, the same problems could arise with the resin matrix materials of these PMCs. It is not clear which specific resin materials will be dominant for PMCs use, but there is a widespread concern regarding all chemicals in the workplace and in the environment.

There are already strong regulations concerning chemical use and handling, but again, the sheer magnitude of the automotive industry is likely to bring such requirements to the forefront of interest and may result in additional legislation. This could result in limitation of the types of resins used and implementation of additional safeguards. The impact is less likely to prevent implementation of PMCs technology than it is to affect the economic viability and timing of the introduction of this technology.

Recyclability

The current recycling of scrap automobiles is a major industry. Sophisticated techniques have been developed for separating the various materials, and cost-effective recycling procedures are an integral part of the total automotive scene. Because steel constitutes 60 percent (by weight) of a current automobile, the recycling of steel is the major portion of the recycling industry. Recycling of PMCs is a radically different proposition, and use of these materials will necessitate development of new industrial recycling processes if large volumes are manufactured.

If PMCs are only applied in low-volume specialty vehicles, however, current recycling techniques of landfill and incineration will probably be adequate.

The potential for large numbers of composite-intensive vehicles to be scrapped will undoubtedly raise the issue of disposal to the national spotlight. One concern is that there would be a disposal problem due to a lack of economic incentives to recycle. Consequently, this problem may need to be addressed by legislation before widespread use of these materials is permitted. The result of such legislation could be the commitment of resources at an early stage of development with payback as part of the overall cost of PMC development.

Crash Regulations

There are regulations in existence, and others proposed, that set or would set impact-survival criteria in frontal impacts, side crash tests, and vehicle-to-vehicle impacts. Various scenarios have been proposed for making these standards more stringent (e.g., raising frontal-impact criteria from 30 to 35 miles per hour, and possibly higher).

Basic experience to date in crash-energy management has primarily been with steel vehicles and, consequently, the specific wording of the regulations is based on the characteristics of these vehicles. Vehicles consisting largely of PMC materials absorb energy by significantly different mechanisms, and the details of impact would be very different from those of steel vehicles, even though the objective of occupant protection would be the same.

Thus, new regulations in this area could contain provisions that would preclude the use of PMCs because of the lack of information. For instance, if a requirement were promulgated that stated no fracture of a major body structure shall occur during a certain impact, PMCs would be excluded because, unlike steels, internal fracture of the PMCs is a critical part of energy absorption. Thus, detailed wording of crash regulations based on steel experience could inadvertently jeopardize the potential use of PMC structural materials.

Fuel Economy Standards

Just as some regulations might produce deterrents to PMCs use, others might promote development and use. If CAFE requirements were drastically increased, there would be a limited number of options for increasing fuel efficiency—downsizing, increased power train efficiency, and weight reduction. In terms of weight reduction, aluminum alloys and PMCs would represent perhaps the major options. Thus, legislation requiring a marked increase in fuel economy might tend to promote the development and use of PMCs, providing that functional requirements, manufacturing feasibility, and overall economic factors are proven.

TECHNOLOGY DEVELOPMENT AREAS

Although years of development efforts have advanced structural composites so that they constitute a significant material for use in the aviation and aerospace industries, the cost-effective use of these materials in the automotive industry requires considerable additional developmental work in the following areas.

Compression Molding

Improvements in SMC technology are required in the areas of reduced cycle times, reproducibility of physical properties and material handleability. A major improvement would be a significant reduction in manufacturing cycle time. Current objectives are to cut the conventional time from 2 to 3 minutes to 1 minute or less. Development of materials requiring less flow to achieve optimum physical properties would permit more reproducible moldings to be made. Other potential technology improvements for SMC include a reduction in the aging time for material prior to molding, an internal mold release in the material, an improved cutting operation to prepare a loading charge for the molding machine, automated loading and unloading of molding machines, and improved dimensional control of final parts.

High-Speed Resin Transfer Molding

There are two critical segments of this process that require major developments to achieve viability. One is reduction in manufacturing cycle time, and new, faster curing resins currently under development should make significant contributions in this area. The other is development of automated preform technology (foam core development and subassembly), which is critical to achieving cost-effectiveness. This is perhaps the area requiring major innovation and invention, but it has yet to be perceived by the existing fiber and fiber-manipulation industry to be a major area for development.

Fiber Technology

There are three major areas in fiber technology that must be optimized to promote fiber use in high-production industries: 1) improved physical properties of the composite, 2) improved fiber handling and placement techniques, and 3) improved high-volume production techniques providing fibers at lower cost. Superior physical properties would result from improved sizings (fiber coatings) to reduce fiber damage during processing and provide improved mechanical properties in the finished components. Fiber-handling equipment permitting high-speed, precise fiber placement with minimal effect on fiber properties is a vital requirement for the development of stable, three-dimensional preforms. Cost minimization is a critical factor in using glass fibers but also should be considered from the viewpoint of generating other fibers (e.g., carbon fibers) at costs amenable to mass-production use.

Joining

Two key areas dominate the category of joining technology. First, adhesives and mechanical fasteners must be tailored for PMC construction, to develop the necessary combination of production rate and mechanical reliability. Second, there is a need for the development of design criteria and design methodologies for adhesive joints. Neither of these areas have been systemically developed for a mass-production industry and far greater attention must be paid to joining materials and to methods for alleviating any problems in this element of the overall PMCs technology.

General Technology Requirements

Design methodologies for use with PMCs to cover all aspects of vehicle requirements must be developed to a degree comparable to current steel knowledge. The ability to tailor PMCs for specific requirements must be integrated into such design guides, and this makes the task more complex than the equivalent guidelines for isotropic materials (e.g., metals). Manufacturing knowledge and experience, which provide constraints for the design process, must be fully documented to optimize product quality, reliability, and cost-effectiveness. The degree of component integration must be a key factor in determining manufacturing rates, and this interdependence of design and manufacturing will evolve only over a protracted time period. This buildup of experience will be the key factor in resolving overall economic factors for the production of composite vehicles.

Standards

The complexity of PMC materials relative to metals will require the development of standard testing procedures and material specifications as is discussed in chapter 5. The rapid proliferation of materials in the PMC arena will not permit final establishment of these generic standards until PMC technology matures. It is likely that specific corporate standards will be used in the interim prior to professional society actions.

SUMMARY

The extension of PMCs use to automotive structures will require an expanded knowledge of the design parameters for these materials, together with major innovations in fabrication technologies. There is abundant laboratory evidence and some limited vehicle evidence that strongly indicates that glass fiber-reinforced PMCs are capable of meeting the functional requirements of the most highly loaded automotive structures. There are, however, sufficient uncertainties (e.g., long-term environmental effects, complex crash behavior) that applications will be developed slowly until adequate confidence is gained. Nevertheless, it seems inevitable that the functional questions will be answered, and it only remains to be seen how soon.

Perhaps the most imperative requirement is the cost-effective development of fabrication techniques. There will be a prerequisite to widespread use of PMCs in automotive structures. High-volume, less-stringent performance components can be manufactured by variations of compression molding techniques. It is the high-volume, high-performance manufacturing technology that needs development, and the HSRTM process appears to be a sleeping fabrication giant with the potential of developing into just such a process.

All the elements for resolving the rapid, high-performance issue are scattered around the somewhat fragmented PMCs industry. It will require the appropriate combination of fiber manufacturers, resin technologists, fabrication specialists, and industrial end users to encourage the necessary developments.

The advent of composite-intensive vehicles will be evolutionary. The most likely scenario would be pilot programs of large PMC substructures as initial developments to evaluate these materials realistically in field experience. This would be followed by low annual production volumes (20,000 to 60,000 units) of a composite-intensive vehicle that would achieve the extensive manufacturing experience vital to the determination of realistic fabrication guidelines and true economics.[29] The data derived from such introduction would determine the potential for high-volume production.

Currently, the industry infrastructure is not in place for PMC-intensive vehicles. In addition, the supply base could presently respond to only low-volume production of PMC vehicles. Neither of these situations is a major restriction in that the anticipated long development time would permit the appropriate changes to occur over a protracted period. Rather, the initial decisions to make the necessary changes and (substantial) financial commitments will have to be based on significant evidence that PMC vehicles are viable economically and will offer customer benefits.

Irrespective of the scenario for the eventual introduction of PMC vehicles, there are probably some general conclusions that can be drawn relative to the impact of these materials. PMC applications are unlikely to have a large effect on the size of the labor force because the major changes are not in labor-intensive areas of vehicle manufacture and assembly. Likewise, the necessary skill levels for both the fabrication of the PMC parts and assembly of the body should not be significantly changed. Engineering know-how would be very different, but the needed skill levels would be similar to those already in place.

Perhaps the largest effect would be on the supply industries, which would need to implement production of PMCs. This would involve both a change in technology for many current suppliers, together with the development of a new supply base. The steel industry would experience a corresponding decrease in output, but the decrease would only be of major proportion if PMC vehicles became a significant proportion of total vehicle output. The repair and recycling industries would similarly undergo a major change to accommodate the radical change in the vehicle materials.

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[29] Ibid.

Chapter 8

Industrial Criteria for Investment

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Chapter 8

Industrial Criteria for Investment

FINDINGS

Aggressive industry investment in the production and use of advanced materials will be one key to the future competitiveness of these industries. Based on extensive interviews, OTA finds that the investment criteria used by advanced materials companies vary depending on whether they are suppliers or users, whether the intended markets are military or commercial, and whether the end use emphasizes high performance or low cost.

Suppliers of advanced structural materials tend to be technology-driven. They are focused primarily on the superior technical performance of advanced materials and are looking for both military and commercial applications. They also tend to take a long-term view, basing their R&D investment decisions on qualitative assessments of the technical potential of advanced materials.

On the other hand, users tend to be market-driven. They focus primarily on short-term market requirements, and they expect to recover their investments within 3 to 5 years.

Frequently, suppliers and users operate in both defense and commercial markets. However, the investment criteria employed in the two cases are very different. Defense contractors are able to take a longer term perspective because they are able to charge much of their capital equipment expenses to the government, and because the defense market for the materials and structures is relatively well-defined. Companies supplying commercial markets, on the other hand, must bear the full costs of their production investments and face uncertain returns. Their outlook is therefore necessarily shorter term. This difference in market perspective has hampered the transfer of defense-oriented materials technology to commercial users, and it underlines the importance of well-defined markets as a motivating force for industry investments in advanced materials.

The many applications of advanced structural materials do not all have the same cost and performance requirements. Accordingly, the investment criteria of user companies specializing in different product areas are different. In general, barriers to investment are highest in cost-sensitive areas such as construction and automobiles, where expensive new materials must compete with cheap, well-established, conventional materials. Barriers are lowest in applications that can tolerate high materials and fabrication costs, such as medical implants and aircraft.

The process of developing a new structural material and manufacturing products from it is very expensive, and may take 10 to 20 years. Most potential users require a payback period not longer than 5 years, and an initial sales volume of $5 million to $50 million per year to justify production investments. In general, commercial end users do not perceive that these criteria will be met by advanced structural materials, particularly in cost-sensitive applications. OTA agrees that these expectations are probably correct; solution to the remaining technical and economic problems will take longer than 5 years. The high risk associated with this market uncertainty is the biggest single barrier to commercial production.

The existence of well-defined markets for new structural materials appears to be a necessary but not sufficient condition to stimulate substantial investments by commercial end users. OTA's industrial respondents identified a number of additional barriers to commercialization that are likely to persist as these technologies and markets mature:

- export controls;
- lack of trained technical personnel;
- tax law changes in 1986, including the removal of investment tax credits and reduced depreciation allowances;
- liability concerns and costs;
- uncertainties associated with government procurement practices, particularly defense regulations and policies;

- time and associated costs of certification testing for advanced materials; and
- threat of technological obsolescence and the inability to obtain a defensible proprietary position.

INTRODUCTION

When a company considers the introduction of a new material into a product, it is likely to pay more attention to the business climate and opportunities for profit than to the specific material used. Moreover, most of the government policies that affect the business climate in which such decisions are made are blind to any particular material or technology.

In this chapter, therefore, a different approach is taken to the subject of advanced structural materials. Instead of focusing on different types of materials, as done in previous chapters, this chapter emphasizes a spectrum of end uses—biomedical, aerospace, automotive, and construction—that span a range of material requirements from high performance to low cost. This emphasis highlights the various factors that affect a company's decision to introduce a new material in these end uses.

The discussion presented here represents a distillation of extensive interviews conducted for OTA with over 75 organizations involved in the supply and use of advanced structural materials.[1] These interviews were supplemented with a workshop held at OTA on December 15 and 16, 1986. The participating organizations, including companies, government agencies, and trade organizations, are listed in appendix 8-1. What emerges is a portrait of the factors considered most important in a company's decision to invest in advanced materials research, development, and production. This information is also used to inform the policy discussion in chapter 12.

CHARACTERIZATION OF ADVANCED MATERIALS SUPPLIERS AND USERS

Private sector interest in advanced materials is pervasive, and the list of key companies spans a wide variety of industries. Advanced materials suppliers include companies with core businesses in chemicals, commodity materials, and defense, whereas the advanced materials users include companies in construction, automotive, aerospace, and biomedical industries. This diversity is the result of three major factors:

1. broad applicability of advanced structural materials to military and commercial products due to their superior performance characteristics and potential for cost savings;
2. opportunities for diversification perceived by those domestic industries facing mature or declining markets and foreign competition; and
3. existence of specific government programs—especially defense programs—that have created a market for advanced materials.

All of the advanced materials supplier companies interviewed considered themselves to be technically sophisticated and motivated by the performance characteristics of advanced structural materials. Even commodity materials companies make a point of saying they address "technology development for our customers" or describe themselves as "engineered materials companies." A sense that advanced structural materials is the "place to be" dispels the lack of hard economic justification for R&D and commercialization investments.

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[1] Technology Management Associates, "Industrial Criteria for Investment Decisions in R&D and Production Facilities," a contractor report for OTA, January 1986.

As one chemical industry executive put it:

> It is not unusual in this business—for that matter in other similar kinds of materials technology businesses—for companies to say, "If the market looks like a $10 billion market 10 years from now, then we are willing to invest in that market without being able to do an accurate assessment of the potential return." We think that we can play technologically—we are a technical-based company. So we are headed in that direction. If the market promises to be big enough, we want to play.

Advanced materials user companies in the construction, automotive, aerospace, and biomedical industries are focused on market needs and cost competitiveness. They put a major emphasis on the use of advanced structural materials to enhance market acceptance of their final products. However, enhanced material performance has value for them only if the potential market places a premium on performance. Otherwise, new structures and processes must demonstrate comparable performance with lower costs compared with the materials in current use.

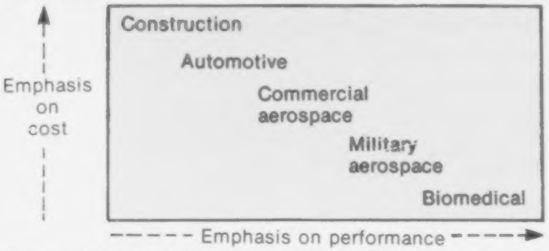
As portrayed conceptually in figure 8-1, cost and performance factors differ in importance among the various industry segments involved. In commercial aerospace, automotive, and construction markets, for instance, acquisition costs and operating expenses are the major purchase criteria, with a progressively lower premium placed on high material performance. In military aerospace and biomedical markets, on the other hand, functional capabilities and performance characteristics are the primary purchase criteria.

The sales potential of advanced materials is greatest in the markets in the center of figure 8-1; e.g., automobiles, and commercial aircraft. Construction materials are used in high volume, but must have a low cost; biomedical materials can have high allowable costs, but are used in relatively low volume. Characteristics of these potential markets for advanced materials are described below.

Construction Industry

The construction industry is extremely fragmented, being made up of many small companies, both suppliers and users. In general, the industry's products are low-cost, high-volume commodities and, except for specialty applications, introduction of new, more expensive products is extremely difficult.

Figure 8-1.—Relative Importance of Cost and Performance In Advanced Material User Industries



Barriers to the use of advanced materials decrease from upper left to lower right.

SOURCE: Technology Management Associates, "Industrial Criteria for Investment Decisions in R&D and Production Facilities," a contractor report for OTA, January 1986.

The construction industry is mature and conservative in nature. Public safety requires long demonstration periods before the adoption of new approaches, and the industry itself has very little to do with the performance specifications. In general, the industry builds a structure that others have specified, to codes and regulations that change very slowly. Furthermore, the retraining of the labor force required to implement new materials and processes may be extensive. Therefore, construction companies are generally not innovative or R&D oriented, and new product developments are relatively rare.

To complicate matters, the current business climate is generally depressed. Construction materials companies have been losing money for several years, and they are taking defensive actions to protect existing markets. In explaining their plight, industry respondents cited a "foreign invasion" of "low-cost imports." Foreign ownership of U.S. construction materials companies is estimated by industry executives to be 40 to 50 percent of the entire U.S. construction materials industry—up from 3 percent 15 years ago. Foreign companies are attracted by the current restructuring of U.S. industry, the strong U.S. technical base, and the very favorable currency exchange rates.

One promising approach to the use of new materials in construction is to use them in repair, maintenance, and rehabilitation of existing structures. In this way, the materials' performance can be evaluated over time without relying on them to sustain the fundamental integrity of the structure. By this means, innovative materials may become integrated into the system and may be considered in the development of new construction codes in the future.

Automotive Industry

The automotive industry companies—a few large automobile manufacturers and a large number of smaller component fabricators and suppliers—are faced with severe price competition. Although greater fuel economy has receded as a driving force for introducing new materials into automobiles, there is continuing interest in potential cost savings from the use of advanced structural materials through both part consolidation and reduced tooling costs.

The industry focuses on R&D that could be commercialized within 5 years; internally funded long-term research programs involving advanced ceramics and composites have been greatly reduced or postponed. For example, industry executives gave the following reasons for their companies having abandoned research on ceramic gas turbine engines:

- "limited fuel economy potential when compared to other available power plants";
- "multifuel possibilities not an asset in the domestic market";
- "no packaging or design flexibility benefits"; and
- "significant technical challenges—not available within the 1990 time frame."

Most of the current R&D is focused on near-term reductions of component costs and production expenses. Some of those cost reductions involve limited replacement of metal components in gasoline engines with ceramic materials. However, as one respondent said:

> Some components produced from advanced materials offer little advantage over conventional metal technology, and the production decision would depend on cost competitiveness.

The automotive industry is conservative in the application of advanced materials technology. From the perspective of advanced materials suppliers, the industry appears interested only in incremental improvements. As one supplier noted:

> When you go to apply a new material to the automobile design problem, the characteristic response is, "We made it in steel. Use the same diagram and give us a new material that we can make into the same equipment and then we'll buy your product." They don't approach the car design from the systems design view as an integrated whole.

Automotive manufacturers require extensive static and fleet testing of new components and a minimum lead time of 3 to 5 years to introduce product innovations. However, it was the view of several materials supplier executives that given a change in attitude, advanced materials could be rapidly adopted by the industry. They noted that in Japan, the use of ceramic fiber-reinforced pistons for small diesel engines progressed in only 3 years from limited production of a specialized Toyota vehicle to use in all diesel engines of that size.

Most materials development for automotive applications is being conducted outside of the three major automakers, by both material and component suppliers—companies that manufacture valves, pistons, and other automotive components. One industry spokesman stated that:

> You will find that a lot of the innovation and a lot of the new design work and new materials work is being done outside of the automobile builders, who are becoming assemblers of components. There is a significant amount of work going on.

Aerospace Industry

Like the automotive industry, the aerospace industry is composed of relatively few large companies that manufacture aircraft, plus many smaller companies that manufacture and supply components. The military market for high-performance aircraft has driven the development and application of advanced materials in the aerospace industry. To a limited degree, use of these materials also carries over into the manufacture of commercial transport aircraft. For instance, composite materials are used in nonstructural components, such as control surfaces, fairings, and trailing edge panels; also, the European consortium Airbus uses composites in primary structural components of its commercial transports, including both vertical and horizontal stabilizers (tail assembly).

Commercial aircraft manufacturers, like automobile manufacturers, are facing stiff competition and are currently seeking to minimize the cost of their commercial products. Use of composite structures offers the potential for reduced aircraft weight and hence lower fuel costs. However, the recent decline in the price of fuel has reduced the attractiveness of composites. The industry attitude toward advanced structural materials R&D and production is reflected in this comment from an aerospace company manager:

> During the era of the Boeing 767, composite materials were worth $300 per pound (in fuel savings over the life of the aircraft); today they are worth $75 per pound (because of lower fuel prices).

For several years there have been intensive efforts to develop and certify general aviation aircraft that make extensive use of advanced composites. Because these aircraft are designed from the start with composite materials and fabrication processes in mind, the composite airframe is likely to be cheaper than a comparable metal airframe. According to one manufacturer in the general aviation market:

> The cost has been driven higher than private users can afford to pay for airplanes. We think that the use of composites can help us get those costs down.

Biomedical Industry

R&D on biomedical applications of advanced structural materials is conducted primarily in orthopedics and dentistry. Companies in this industry make specialty products to solve medical or laboratory problems. Technical superiority or innovation confers an important competitive advantage and is the primary motivation for continued R&D. Fourteen of the fifteen companies interviewed currently have active R&D programs that are strongly product-oriented and market-driven.

In the dental and orthopedic segments, reduction of the cost of components or of product fabrication are not particularly important motivations for R&D because these costs are usually passed on to the customer. Furthermore, the actual cost of the product is small compared to the cost for the professional services (medical and dental fees) required to install the product.

In contrast to the automotive and construction industries, which are static or declining, the advanced biomedical materials industry is rapidly expanding. Advances in materials as well as advances in basic medical and dental research make this a rapidly moving field, so that products tend to last only a few years. This fuels the competitive pressure to invest in additional R&D.

R&D efforts are focused primarily on material evaluation, certification testing, and fabrication technology development. Most companies do not develop new materials. Rather, materials originate outside the biomedical industry—e.g., from aerospace materials suppliers. However, because the quantity of materials used in dental and orthopedic applications is so small, many such suppliers have not cultivated the biomedical market.

INDUSTRIAL DECISION CRITERIA FOR R&D AND PRODUCTION

The criteria used by industry sources interviewed by OTA fall into two groups, depending on whether the respondents represent suppliers or users. Suppliers of advanced structural materials tend to be technology driven—they focus primarily on superior technical performance of advanced materials and look for applications. Users tend to be market—driven—they focus primarily on market requirements.

There are two factors, however, that tend to blur this distinction. First, advanced materials suppliers are often supported partially or wholly by military contracts, and thus they have the luxury of focusing on high-performance materials for the long term. Second, R&D expenditures are typically an order of magnitude less than production expenditures; thus, while suppliers spend more freely on R&D than end users, both users and suppliers tend to focus on market-related criteria in making production investment decisions.

As pointed out by one executive from a company that is both a ceramic materials supplier and component manufacturer, companies must make investment decisions all along the spectrum from basic research through production:

> The decisionmaking process changes dramatically depending on where you are in R&D and whether or not you're ready to go into production. In the research phase, numbers are pretty soft—you identify an opportunity and make a small investment by comparison to later phases. As you move up that curve to the development phase, you're dumping a lot more money in. When you make that final decision to go into production, you're talking about the big bucks and you want to have as hard a number as you can get your hands on.

R&D Investment Criteria

The major criteria employed by suppliers and users of advanced materials to assess R&D and production investments in advanced ceramics and composite materials are indicated in table 8-1. The more technology-oriented criteria are listed toward the top, and the more market-oriented toward the bottom.

Very few of the suppliers interviewed purported to use typical business assessment tools (e.g., return on investment) in selecting and ranking advanced materials R&D projects. Although some executives indicated that potential market size was considered, most often they used preliminary estimates merely as an order of magnitude indication of the potential market. A typical attitude was:

> If you estimate market size—you'll quit. We don't know the ultimate markets yet. Discounted cash flow methods will tell you to get out of advanced ceramics research—you have to operate on faith that a ceramics market will develop.

Table 8-1.—Industry Investment Decision Criteria

	Materials suppliers		Materials users
Decision criteria	R&D	Production	R&D and production
Corporate technical capabilities	★		
Material performance characteristics	★		★
Fit with corporate strategy	★		
Competitive threats	★		
Threat of technical obsolescence		★	
Sales volume: • Market volume • Market share		★	★
Return on investment or assets		★	★
Timing: • Payback period • Time to market			★

★Indicates major investment criteria.

The more technology-oriented criteria are listed toward the top, and the more market-oriented toward the bottom. As a group, suppliers apply more qualitative, technology-oriented criteria to R&D investment decisions than users do. However, both suppliers and users apply quantitative, market-oriented criteria to production investment decisions.

SOURCE: Technology Management Associates, ''Industrial Criteria for Investment Decisions in R&D and Production Facilities,'' a contractor report for OTA, January 1986.

The attitudes of advanced materials suppliers and users toward the investment criteria listed in table 8-1 are discussed below. The technical capability of the company—viewed both in terms of research resources and production experience —was the criterion for R&D investment most often mentioned by materials suppliers. It is a general industry view that success in materials R&D is to a great extent dependent on technical experience and the existing corporate technology base, including facilities, personnel, and equipment. Highest priorities go to R&D projects that build on the corporation's technical experience in related materials research and production.

Some corporations without the technical capability to participate in specific aspects of advanced materials R&D obtain the necessary capabilities by hiring personnel, corporate acquisitions, or joint ventures. Many companies also supplement their R&D capabilities by participating in collaborative efforts with universities and Federal laboratories. Although some corporations feel that this is an appropriate R&D investment, results are considered "spotty," and many companies feel that the most beneficial aspect of the collaborative programs with universities is access to top-quality students. (This view is consistent with the analysis of university/industry collaborative programs in ch.10.)

Corporate consideration of the potential materials performance characteristics reflects an interest in material functions that have a higher value, such as thermal stability or strength. Both suppliers and users cited superior performance characteristics as a principal motivation for R&D investments. However, most of the user companies in the aerospace, automotive, biomedical, and construction industries conduct R&D that is closely tied to near-term production, such as material evaluation, fabrication technology development, and certification or qualification testing.

Many companies also use "fit with corporate culture" as a criterion for R&D investment. Suppliers identify themselves as "an engineered materials producer," "a chemical company's chemical company," or in other similar terms that are consistent with the high-technology culture. A proposed R&D project that does not fit with this corporate image is often abandoned.

Some companies, concerned that their competitive position may change, pay close attention to the materials R&D that other companies are conducting. Many companies have made a conscious decision to maintain a technical lead in specific markets (e.g., aerospace) and conduct R&D to keep ahead of the competition. One supplier of composite materials indicated that:

> . . . more improvements have been made in thermosetting composites in the last 12 months than in the last 10 years to compete with thermoplastic composites, because it looked like the Air Force was going to be inclined to use thermoplastics (for the Advanced Tactical Fighter).

Production Investment Criteria

Although suppliers and users are not all in agreement about the timing and amounts of capital to invest in production facilities, most companies agree that the production decision depends on three major criteria: the threat of technological obsolescence, potential sales volume, and return on investment.

The threat of technical obsolescence is an important criterion in the production decision. Materials suppliers are concerned, for instance, that a facility could become uneconomical due to a significant advancement in production technology, or that a technically superior product could displace the company's own product in the market.

Suppliers interviewed indicated that an initial sales volume of $50 million to $200 million would be necessary to induce investment in a new production facility. However, most companies also expect the potential for that sales volume to grow to $1 billion in 10 years.

For some suppliers, such as manufacturers of aerospace composite materials, the production decision is simplified. If the company's products are qualified by the military for specific programs, such as the Advanced Tactical Fighter program, then the total market for composites can be estimated with reasonable certainty by using some judgment based on the number of other composites that are also qualified (an indication of market share).

Potential sales volume is also a very important criterion for materials users in evaluating both R&D and production investments. Initial sales volume requirements range from $3 million to $5 million among biomedical companies to $50 million to $100 million in the automotive and aerospace industries.

The potential return on investment (ROI) is an important criterion in the production decision for both suppliers and end users. The after-tax ROI required by supplier companies ranges from 10 to 30 percent. This range reflects corporate assessments of potential risks and uncertainties in the market. Suppliers of advanced materials to the military have generally lower ROI criteria—10 percent—whereas chemical and materials companies selling in commercial markets require higher ROIs—20 to 30 percent. However, this comparison may be somewhat misleading in that military contractors have traditionally been able to charge a significant amount of their development costs to the government instead of taking them out of sales, as in the commercial case.

The market timing criteria employed by commercial end users of advanced materials interviewed by OTA varied significantly with industry. The aerospace industry generally has a longer term view than most other end users, and timing is not a major factor in either R&D or production investment decisions among military aerospace companies. However, as a group, end users require that capital equipment costs be recovered in a shorter time than do the materials suppliers. Most end users require a payback period of 3 years or less, with profits in less than 5 years, before investment in production would be considered.

BARRIERS TO COMMERCIALIZATION OF ADVANCED MATERIALS

Although a diverse array of companies from various industries are involved in R&D and commercialization of advanced structural materials, some common themes emerged when industry executives were queried about the reasons why they would hesitate to establish new R&D programs or commercialize new products involving advanced ceramics or composite materials. The perceived barriers were somewhat different depending on whether the intended market was military or commercial.

In the case where the government is the customer for both R&D and advanced materials products (especially military programs), market uncertainties are reduced, and the planning horizons of materials suppliers and manufacturers are much longer. As one supplier of composite materials noted:

> A distinction needs to be made between an industry in which the government is a strong driver and a major customer, such as the aerospace industry, which has been a champion of composite materials—a truly long term commitment—and the part of the economy which depends on the general market situation.

Among commercial end users, the profits that could be projected within the planning horizons of the company in most cases do not justify the near-term production costs. Advanced materials involve a long and costly commercialization process in a business environment that often requires a short-term focus; moreover, the currently depressed business climate in certain sectors of the economy—including construction, automobiles, and general aviation aircraft—results in a preoccupation with protecting existing businesses.

Representative of industry views was the following comment made by an advanced material supplier to the aerospace industry:

> There is a long gestation period—between the time that you develop a product, have it qualified, and when you sell it. A company has to have done it before or the management will probably get very impatient, because the R&D and qualification is done 3 to 5 years before the purchase. That is different from the commercial polymer business where you can start seeing some sales in a year or two. A company has got to be patient, and most companies are not.

Observed one advanced ceramic supplier and component manufacturer:

> In the truly private sector of the economy, a strong case can be made that a short-term preoccupation with cash flow has made it difficult for material suppliers and component manufacturers.

Within this context of two very different market situations, military and commercial, several common barriers to production of advanced materials and structures were cited in industry interviews. These include: 1) the lack of an adequate experience base and data on the mechanical and processing properties of materials; 2) the lack of a suitable technology infrastructure for guaranteeing that advanced materials with specified properties can be produced; and 3) insufficient numbers of trained materials scientists and engineers. In addition, the high cost and long lead time associated with the safety and performance certification of new materials was perceived as a problem in both the biomedical and aerospace sectors.

On the other hand, the different market situations also led to some different perspectives on the principal barriers to investment. Not surprisingly, the defense-oriented side of the industry tends to single out defense policy-related concerns, while the commercial side cites broader economic and government policy concerns. These are discussed below.

Concerns of Defense-Oriented Suppliers and Users

The role of the Department of Defense in the R&D and production of advanced materials and structures is explored in detail in chapter 11. Here, however, it is appropriate to note some of the more commonly expressed industry attitudes.

Export restrictions and controls reduce the competitive position of U.S. companies abroad and can result in investment in production facilities outside of the United States.

Industry executives view government policy on the export of advanced materials as a major barrier to commercialization because it limits the ability of U.S. businesses to compete globally. Government delays in processing license applications, for instance, raise the costs of delivering the product to the market. Non-U.S. customers do not want to do the paperwork.

One supplier of composite materials declared:

> If I have to ask my customer to go to his government to get an import certificate so I can go to my government to get an export certificate, it just costs both of us money, plus the hassle and the time . . . If I sell him the same material four months from now, we go through the whole show again.

Another supplier of composite materials made this point:

> Carbon fiber and carbon fiber-based prepregs are technologies that are freely available in Europe and the Pacific, yet a U.S.-based company shipping overseas must apply for an export license for technology and for product.

In addition, in the carbon fiber case, export licensing requirements place U.S. companies at a further disadvantage in foreign markets. A European aircraft manufacturer that buys carbon fiber prepreg material from a U.S. company must get permission from the U.S. Government to export the finished airplane. If the same European company buys from another supplier in Europe or Japan, the paperwork and U.S. restrictions can be avoided.

One consequence is that U.S.-based firms making composite materials have transferred production to Europe to supply European customers to avoid "messing with the bureaucracy." One advanced ceramics component manufacturer interviewed by OTA indicated that the U.S. requirements for export licensing of machined components have also resulted in U.S. ceramics corporations setting up component finishing shops in Europe to avoid the paperwork.

Delays in shipping caused by the necessity of going through the export license process gives the appearance that U.S. companies are unresponsive to market needs. Furthermore, as one supplier of ceramic materials noted:

> When we must file a statement with the Department of Commerce that describes the intended use, our customers complain about loss of confidentiality.

Industry interviews also indicated that the private sector is concerned over the inconsistencies in the overall Federal export policy. One source complained that:

> The Department of Commerce encourages exports and the Department of Defense restricts them.

Differing Federal standards among government agencies slow the commercial introduction of military technology.

Different standards, approaches, and experience levels of regulatory agency personnel can inhibit the transfer of technology from the military/defense arena and government space programs to private sector applications. In aerospace applications of advanced composite materials, for instance, one industry executive identified a key issue:

> Materials that spin out of the military aerospace programs (and supposedly are well-characterized or qualified for military applications) must be retested for the Federal Aviation Administration (FAA).

Aerospace industry executives suggested that FAA acceptance of military-qualified materials and applications could be enhanced by the accelerated development of a military specification handbook for advanced materials, comparable to the currently accepted Military Handbook 5 for metals. Such an effort is in fact under way. Military Handbook 17 on composite materials is currently under development by the Army Materials Laboratory in Watertown, MA.

Some executives, though, doubted that the availability of such standards would reduce the testing required by individual aerospace companies. As executives from the aerospace and advanced composite supplier fields stated the problem:

- "every corporation has its own specifications";
- "companies will not accept data from anybody else";
- "aerospace companies will not share their data"; and
- "if you've got six people vying for a military contract, you will have to qualify that given material six times."

Government procurement practices may discourage some advanced materials developers from participating in government markets.

Some industry executives voiced specific concerns over certain procurement policies and practices which they encounter in the Federal sector. In particular, the following issues were raised in interviews and at the OTA workshop: 1) procurement contracts are made with more than one source, which may force a company to share its technology with its competitors; 2) awards are customarily made to the lowest bidder, which favors existing suppliers and materials over new suppliers and materials; and 3) there is too much burdensome red tape.

These issues were identified in interviews with every company that participates or has attempted to participate in government programs. Those companies that have been major suppliers to the military consider these issues "just the cost of doing business." However, some companies trying to enter the government market identified them as real concerns. In fact, some companies, particularly in the biomedical industry, have decided to avoid government programs for these reasons.

A further issue is that government policies intended to assure domestic supply of scarce or strategic feedstocks may actually inhibit private sector investment. For example, the Title III program in the Defense Production Act (64 Stat. 798) permits the government to mitigate shortages of critical materials through purchasing mechanisms.

One advanced ceramics materials supplier described the private sector investors' problem in this manner:

> You have an investment plan all ready to put before the board and here the government is coming in with a big attack on the issue. They're going to create multiple sources for domestic production. What should you do? You are interested in that business and you see that the government is going to throw money at a program which you might have a chance to get, and you know your competitors are going to be looking at. What do you do? You wait.

Concerns of Commercial Market-Oriented Suppliers and Users

Liability issues increase the risk and cost of development programs.

The manufacturer's liability in the event of product failure is a disincentive to innovation for advanced materials suppliers and for users in all industry segments. In the construction industry, for instance, long demonstration periods are required to gain user and consumer confidence in the safety of new or innovative materials.

In other industry segments as well, liability protection, or extensive pre-testing to guard against liability, is one of the biggest costs in the introduction of new products. In the words of one supplier of ceramic materials:

> The automotive industry is conservative, and very sensitive to the failure of a supplier's part that will cause General Motors to be liable for work under warranty. Extensive testing is required and must project well below 3 percent failure rate to be within the automotive manufacturers' warranty limits.

A user of advanced biomedical materials made this observation:

> The government has to fix the liability problem—it's the biggest cost. Industry has been very responsible; no company would knowingly put

> out an unsafe product. With most prostheses that break, it's a medical problem, not a materials or fabrication defect.

Added a user of advanced composites in the manufacture of general aviation aircraft:

> Liability costs have gotten to the point where the private user cannot afford to buy a new airplane. The minute an airplane goes out the door, the customer has to pay around $70,000 and that just supports our legal efforts.

Patent protection is a major issue for some advanced materials companies.

For many of the companies involved in advanced materials—especially manufacturers of advanced ceramic components—their inability to protect their patent position is a factor that inhibits investment in R&D and commercialization programs in advanced materials. A representative point of view, as expressed by a supplier of ceramic materials, is as follows:

> Ceramic component manufacturers have no way to protect processes with patents. A process patent law that will cover ceramic component fabrication technology is needed. Current infringements go unpunished.

However, several materials suppliers and users throughout all industry segments tend to disregard patents. One ceramic component manufacturer feels that patents are not very useful, noting that:

> . . . patents today may not be worth much 5 years from now because technology is advancing so rapidly.

Recent changes in the tax laws may create significant barriers to R&D investment.

Changes in the tax laws in 1986 are likely to affect both suppliers and users of advanced materials. Industry executives cited several changes that may directly inhibit investments in R&D and the markets for products containing advanced materials. Chief among their complaints were the removal of investment tax credits and reduced depreciation allowances. On the other hand, one supplier of ceramic materials components pointed out that:

> . . . if you look to the tax situation as a decision-maker, you're making a mistake, because what the government can give they can take away in the next Congress. Any advantage due to the current tax situation can erode.

Changing product certification requirements can place a competitive disadvantage on market leaders.

Testing for product certification—primarily to meet government requirements—was one of the specific inhibitory factors cited most often both by suppliers and users, particularly in the aerospace and biomedical industries. Certification and licensing requirements contribute heavily to both development costs and the time required for R&D and commercialization. For example, in the words of one composites supplier to the aerospace industry:

> It costs $1 million to get a new fiber and prepreg certified through the Federal Aviation Administration, and it could take 10 years.

A supplier of ceramic materials made this comment:

> Acceptance testing for ceramic materials takes too long—on the order of 7 years for many applications. The expense is not the key—it's the time.

And a user of advanced biomedical materials complained:

> The biggest impediment is the Food and Drug Administration (FDA). Testing and retesting every small improvement takes time and money.

Certification expenses can include both the direct costs associated with testing a material or retesting a military-qualified material, as well as the indirect costs of "educating" personnel in Federal regulatory agencies, such as FDA and FAA. Companies that are first to market may be at a competitive disadvantage if "close follow" companies can avoid some of the costs and delays by marketing a very similar product.

A good example of this principle is advanced materials R&D in the biomedical industry. Biomedical products introduced after the 1976 Food and Drug, Device and Cosmetics Act (Public Law 94-295) that are "substantially equivalent" to products classified by FDA before 1976 can be sold on the open market on the basis of a short approval application. However, manufacturers of new technologies, such as advanced ceramic or composite implants, are required to file an "Investigational Device Exemption" (IDE) and to carry out expensive preclinical and clinical trials. After 2 to 3 years, the company may seek FDA approval of that specific product on the basis of the clinical trials.

In theory, each additional company with a similar product also has to go through the same IDE process. However, FDA may change the status of a material if clinical evidence shows that the material is safe. Once the material is reclassified, other companies seeking to market products made from the material for essentially equivalent applications need only file a short statement of the material's safety record. Therefore, every innovative leader must perform expensive tests to prove its product is safe to win FDA approval, but at the same time it risks wasting its investment in development and testing.

In summary, the concerns identified above constitute significant barriers to companies seeking to produce ceramic and composite products for commercial markets. However, the principal barrier remains the fact that investments in advanced materials R&D and production do not meet the cost/benefit criteria of most U.S. commercial end users today. Thus, there is very little commercial market pull on these technologies.

At the same time, it is important to recognize that some foreign competitors do not apply the same cost/benefit criteria to their investments; rather, they take a longer term "technology push" approach, and they are prepared to sacrifice near-term profits to obtain the experience in manufacturing with advanced materials necessary to secure a greater share of the long-term markets. This theme is developed further in the next chapter.

APPENDIX 8-1: ORGANIZATIONS INTERVIEWED

Corporations:

Aluminum Co. of America—Alcoa Laboratories
Aluminum Co. of America—Ceramics Division
AMOCO Performance Products Inc.
BASF Corp.—Celion Carbon Fibers Division
Beech Aircraft Corp.*
Biomet Inc. Research and Development
Blasch Precision Ceramics Inc.
Boeing Commercial Airplane Co.
Business Communications Co., Inc.
Calciteck Inc.
Calmat Co.
Cannon Publishing—Medical Devices and Diagnostic Industry
Ceiba-Geigy Corp.—Plastics and Additives Division
Champion Spark Plug Co.—Ceramics Division
Chrysler Corp.—Metallurgical Development Department
Concrete Technology Corp.—R&D
Coors Biomedical Co.
Coors Porcelain Co.
Dentsply International Inc.
DePuy Co.
Douglas Aircraft Co.
Dow Chemical Co. USA—Central Research
Dow Chemical Co. USA—Ceramics
Dow Corning Corp.—Advanced Ceramics Program
Du Pont Co.
Dural International Corp.
DWA Composite Specialties, Inc.*
Dynamet Technology, Inc.*
Ferro Corp.—Commercial Development
Fiberglass Structural Engineering Co.
The Garrett Corp.
General Dynamics Corp.
General Motors Corp.—AC Spark Plug
General Motors Corp.—Detroit Diesel Allison
Genstar Stone Products Co.
Grumman Corp.—Aircraft Systems*
Hercules, Inc.—Graphite Materials
Hexcel Corp.
Howmedica, Inc.
Hysol Grafil Co.
ICI Fiberite
Integrated Polymer Industries, Inc.
Johnson & Johnson—Dental Products Co.
Kaiser Cement Corp.
Kerr Sybron
Lockheed Corp.
Lone Star Industries, Inc.
McDonnell Douglas Corp.—Aerospace

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*Workshop participants whose comments are reflected in this chapter.

Mobay Corp.
Northrop Corp.—Aircraft Division
Norton Co.*
Orthomatrix
Owens-Corning Fiberglass Corp.—Technical Center
PPG Industries, Inc.
Price Brothers Co.
Richards Medical Co.
Salt River Project—Structural Engineering
Shell Chemical Co.*
SOHIO Engineered Materials Co.—Structural Ceramics Division
Stanley Structures, Inc.
Sterling Winthrop Research Institute
Techmedica, Inc.
3M Co.—Health Care Group Laboratory
Transpo Industries, Inc.—R&D
Union Carbide Corp.—Specialty Products Group
Westinghouse Electric Corp.—Advanced Energy Systems Division
Westinghouse Electric Corp.—R&D Materials Science Division
Wiss-Janney-Elstner Associates

Government agencies:

Federal Highway Administration—Paving Materials
National Bureau of Standards
National Institutes of Health—Division of Research Services
State of Connecticut—Department of Transportation
State of Texas—Highway Department
U.S. Department of Commerce—Chemicals Group
U.S. Department of Commerce—Non-ferrous Metals Division
U.S. Department of Energy—Oak Ridge National Laboratories
U.S. Department of Energy—Argonne National Laboratories
U.S. Army Corps of Engineers

Industry trade groups and advisors:

ACI Concrete Materials Research Council
American Concrete Institute
American Society of Civil Engineers
Mount Sinai Medical Center*
National Ready Mix Concrete Association
Portland Cement Association
Prestressed Concrete Institute
Suppliers of Advanced Composite Materials Association
U.S. Advanced Ceramics Association

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*Workshop participants whose comments are reflected in this chapter.

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Chapter 9

International Business Trends

FINDINGS

Several worldwide trends are apparent in the evolving advanced materials industries. These include a shift toward larger, more integrated companies, the growing multinational character of these companies, and increasing government support for development of advanced materials technologies.

In the long run, large integrated materials companies are likely to dominate the high volume markets for advanced materials. One reason is that the capital costs of scale-up and production are higher than most small companies can afford. Also, the close relationships between design, manufacturing, and quality control demanded by advanced materials are more consistent with the capabilities of a large, vertically integrated company. Because most of the value added in advanced materials businesses lies in the production of components and shapes, there is an economic incentive for suppliers of powders, resins, or fibers to vertically integrate into these downstream businesses.

Even so, small companies will also be an important force in advanced materials technology developments. Indeed, because current demand is primarily for research services or limited production of specialty materials for military use, small companies are already playing a major role in advanced materials development, especially in the area of metal matrix composites. Even among the large companies involved, their advanced materials divisions are typically minor sidelights of the main businesses. In the future, small companies will continue to be a source of innovative materials and processes and will continue to supply niche markets too small to attract the large integrated companies.

Through acquisitions, joint ventures, and licensing agreements, advanced materials industries have become markedly more international in character over the past several years. This tends to increase the rate of technology flow across national borders, creating new challenges and, potentially, new opportunities for U.S. companies. This trend also poses problems for the U.S. military, a major consumer of advanced materials, as it attempts to limit the dissemination of these technologies for national security reasons.

Throughout the world, government support for advanced materials development has been steadily increasing. These materials are seen as essential both to national economies and to national defense. Government programs can have a major impact on industry spending, by providing coordination, R&D funding, and markets, especially through the military. However, the real determinant of long-term commercial success is likely to be the commitment of the companies themselves.

Ceramics

The U.S. market for advanced ceramics in 1985 was about $1.9 billion (no data were available on U.S. production). Advanced ceramic production in Japan and Western Europe in 1985 were $2.3 billion and $0.5 billion respectively. In each of these three geographic regions, electronic or optical applications, such as capacitors, substrates, integrated circuit packages, and fiber optics, accounted for over 80 percent of the total. Structural applications, including wear parts, tools and accessories, and heat-resistant products, accounted for the remainder.

By a margin of nearly 2 to 1, the U.S. ceramics companies interviewed by OTA felt that Japan is the world leader in advanced ceramics R&D. Without question, Japan has been the leader in actually producing structural ceramic products for both industrial and consumer use. Japanese end users exhibit a commitment to the use of these materials not found in the United States. This commitment is reflected in the fact that although the U.S. and Japanese governments spend comparable amounts on ceramics R&D (roughly $100 million per year), Japanese industry spends far more on such R&D than does U.S. industry.

Japanese ceramics companies are far more vertically and horizontally integrated than U.S. companies, a fact that probably enhances their ability to produce higher quality ceramic parts at lower prices. However, these companies are probably still losing money on the structural ceramic parts they produce. This commitment reflects the long-term optimism of Japanese companies regarding the future of ceramics technologies.

The Japanese market for structural ceramics is likely to develop before the U.S. market. Ceramics technology already has a high profile in Japan, due in part to the Japanese industry strategy of producing low technology consumer goods, such as scissors and fish hooks, using high technology materials and processes. The overall goal of this strategy is the development of a high-technology manufacturing base to capture larger ceramics markets in the future.

Given the self-sufficiency of the Japanese ceramics industry, the Japanese market is likely to be difficult to penetrate by U.S. suppliers. In contrast, Japanese ceramics firms, which already dominate the world markets for electronic ceramics, are strongly positioned to exploit the U.S. market as it develops. One such firm, Kyocera, the largest and most highly integrated ceramics firm in the world, has already established subsidiaries and, recently, R&D centers in the United States.

West Germany, France, and the United Kingdom all have initiated large government programs in advanced ceramics R&D. West German companies have the strongest position in powders and finished products. Meanwhile, the European Community (EC) has earmarked $20 million for advanced ceramics research through 1989. Although Western Europe appears to have all of the necessary ingredients for its own structural ceramics industry, both the United States and Japan have a strong foothold in the European market for electronic ceramics.

Polymer Matrix Composites

The production value of finished advanced polymer matrix composite (PMC) components produced worldwide in 1985 was approximately $2.1 billion, divided roughly as follows: the United States, $1.3 billion; Japan, $200 million; and Western Europe, $600 million. The U.S. and European markets are dominated by aircraft and aerospace applications, while the Japanese domestic market is primarily in sporting goods. In the United States, advanced composites development is driven by military programs, while in Europe, advanced composites are predominantly used in commercial aircraft.

On the strength of its military aircraft and aerospace programs in PMCs, the United States leads the world in PMC technology. Due to the attractiveness of PMCs for new weapons programs, the military fraction of the market is likely to increase in the near term. However, due to the high cost of such military materials and structures, they are not likely to be used widely in commercial applications.

The commercial application of PMCs is an area where the United States remains vulnerable to competition from abroad. U.S. suppliers of PMC materials report that foreign commercial end users (particularly those outside the aerospace industry) are more active in experimenting with the new materials than are U.S. commercial end users. For example, Western Europe is considered to lead the world in composite medical devices. The regulatory environment controlling the use of new materials in the human body is currently less restricted in Europe than in the United States.

France is by far the dominant force in PMCs in Western Europe, with sales greater than all other European countries combined. West Germany, the United Kingdom, and Italy make up most of the balance. The commercial aircraft manufacturer, Airbus Industrie, a consortium of European companies, is the single largest consumer of PMCs in Western Europe. At the European Community level, significant expenditures are being made to facilitate the introduction of PMCs into commercial applications. In addition, the EUREKA program called Carmat 2000 proposes to spend $60 million through 1990 to develop PMC automobile structures.

In the past few years, the participation of Western European companies in the U.S. PMC market has increased dramatically. This has occurred primarily through their acquisitions of U.S. companies, a move that appears to reflect these companies' desire to participate more directly in the U.S. defense market and to establish a diversified, worldwide business. One result is that Western European companies now control 25 percent of resins, 20 percent of carbon fibers, and 50 percent of prepreg sales in the United States. A secondary result of these acquisitions is likely to be the transfer of U.S. PMC technology to Western Europe, such that Europe will eventually be less dependent on the United States for this technology.

Although Japan is the largest producer of carbon fiber in the world, it has has been only a minor participant to date in the advanced composites business. One reason is that Japan has not developed a domestic aircraft industry, the sector that currently uses the largest quantities of advanced composites. A second reason is that Japanese companies have been limited by licensing agreements from participating directly in the U.S. market.

Metal Matrix Composites

No estimates were available to OTA of the value of current MMC production in the United States, Japan, and Western Europe. The principal markets for MMC materials in the United States and Western Europe are in the defense and aerospace sectors. Accordingly, over 90 percent ($154.5 million of $163.6 million) of the U.S. Government funding for MMC R&D between 1979 and 1986 came from DoD.

The structures of the U.S. and European MMC industries are similar, with small, undercapitalized firms supplying the formulated MMC materials. Some analysts feel that the integraton of the small MMC suppliers into larger concerns having access to more capital will be a critical step in producing reliable, low-cost materials.

Currently, the most common matrix used is aluminum. The large aluminum companies have active R&D programs under way, and they are considering forward integration into MMCs. There are also in-house efforts at the major aircraft companies to develop new composites and new processing methods.

Unlike their small, undercapitalized counterparts in the United States and Western Europe, the Japanese companies involved in manufacturing MMCs are largely the same as those involved in supplying PMCs and ceramics; i.e., the large integrated materials companies. Another difference is that Japanese MMC suppliers focus primarily on commercial applications, including electronics, sporting goods, automobiles, and aircraft and aerospace structures.

One noteworthy Japanese MMC development is the introduction by Toyota of a diesel engine piston consisting of aluminum locally reinforced with ceramic fibers. This is an important harbinger of the use of MMCs in low-cost, high-volume applications, and it has stirred considerable worldwide interest among potential commercial users of MMCs.

INTRODUCTION

Advanced structural materials technologies are becoming markedly more international in character. Through acquisitions, joint ventures, and licensing agreements, the firms involved are seeking both access to growing worldwide markets and ways of lowering their production costs. Governments around the world are investing large sums in multi-year programs in collaboration with industry to facilitate commercial development. Critical technological advances continue to come from other countries; e.g., carbon fiber technology from the United Kingdom and Japan, weaving technology from France, and hot isostatic pressing technology from Sweden.

This trend toward internationalization of the technology has many important consequences for U.S. Government and industry policymakers. The United States can no longer assume that it will dominate the technological advances and the applications resulting from them. The influx of foreign technology may be just as significant in the future as that flowing out. Moreover, the increasingly multinational character of materials industries suggests that the *rate* of technology flow among firms and countries is likely to increase in the future. For the United States as for other countries, it will not be possible to rely on a superior research and development capability to provide the advantage in developing commercial products. Rather, if the technology infrastructure is not in place for quickly appropriating the results of R&D for economic development, those results will first be used elsewhere.

The consequences of globalization of advanced structural materials technologies are perhaps most starkly important for military policy. Military programs are often responsible for the initial development and use of new materials in the United States, and all indications are that the involvement of the military is likely to increase in the future. The military has an interest in preventing the flow of this technology to unfriendly countries, and in securing domestic sources of the materials involved. Both of these interests are complicated by the globalization of the industry. Attempts to erect barriers to the international transfer of technology may result in the United States being bypassed both in the technology and in market opportunities abroad. In effect, U.S. military interests, which are based on a national perspective, are on a collision course with U.S. commercial interests, which have taken on an international aspect. The consequences of increasing military activity in advanced materials R&D are discussed more fully in chapter 11.

This chapter presents a comparative analysis of advanced structural materials industry trends in the United States, Western Europe, and Japan. These regions were chosen because they appear to have the strongest government and industry programs for developing and applying advanced materials. The changing industry structures and relationships with government institutions are examined to illustrate the factors that will determine the relative competitiveness of advanced materials users and suppliers in the future. Data for this chapter were gathered through extensive interviews with government and industry personnel, as well as through literature and computer database searches.[1] [2]

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[1] Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," a contractor report prepared for OTA, Jan. 28, 1987.

[2] Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

CERAMICS

The value of advanced ceramics consumed in the United States, and produced in Japan and Western Europe in 1985 is estimated in table 9-1. (No data were available on U.S. production.) Electronic applications for advanced ceramics, such as integrated circuit packages and capacitors, are considerably more mature than structural applications, and accounted for at least 80 percent of total production. Structural ceramics of the type considered in this assessment accounted for the remainder. This dominance of electronic markets over structural markets is likely to prevail into the next century.[3]

Comparisons among advanced ceramics markets in these three regions are complicated by two factors. First, there is little agreement on what categories of ceramics should be considered "advanced"; Japanese estimates tend to include additional categories, such as alumina catalyst supports, that are normally excluded in Western calculations. Thus, it is important to specify the categories being included along with the numbers. A second factor is that the current U.S. Standard Industrial Classification (SIC) codes used to collect industry performance statistics are too broad to distinguish advanced ceramics from traditional ceramics, such as tableware. Thus, the United States has no reliable index with which to track the performance of its advanced ceramics

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[3] Greg Fisher, "Strategies Emerge for the Advanced Ceramics Business," *American Ceramic Society Bulletin*, vol. 65, No.1, January 1986.

Table 9-1.—Value of Advanced Ceramics Consumed in the United States, and Produced in Japan and Western Europe in 1985 ($ millions)

Region	Electronic[a] applications	Structural[b] applications	Total
United States[c]	1,763	112	1,875
Japan	1,920	360	2,280
Western Europe	390	80	470

[a] Includes packages/substrates, capacitors, ferrites, piezoelectrics, resistors.
[b] Includes automative parts (pistons, liners, valves, bearings), cutting tools, industrial (bearings, seals, microfilters, grinding media for ball mills, sandblast nozzles, sensors), aerospace parts (space shuttle tiles, etc.), and bioceramics.
[c] Consumption in 1985.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987; and Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," a contractor report prepared for OTA, Jan. 28, 1987.

industry. This contrasts sharply with the situation in Japan, where the Ministry of International Trade and Industry (MITI) publishes detailed advanced ceramics production figures each month, broken out by category and including import and export activity. The need for better statistical information on the U.S. advanced ceramics industry is discussed further in chapter 12.

United States

Today, the U.S. advanced ceramics industry faces major challenges from foreign competition. Over the past decade, the U.S. share of the world markets for electronic ceramic components, which constitute about 80 percent of total advanced ceramics markets, has largely been lost to Japan. The race to commercialize advanced structural ceramics is still being run; however, there is ample reason for concern about the outcome. For instance, in spite of large Federal programs aimed at development of ceramic engine components beginning in the early 1970s, and substantial ceramic R&D efforts within the U.S. automobile companies and their suppliers, Detroit has yet to introduce a U.S.-made structural ceramic component in a production automobile. This situation contrasts sharply with that in Japan, where Nissan began introducing ceramic turbocharger rotors in 1985.

The future competitive position of U.S. companies is likely to depend on several factors, including company size and level of integration, participation in cooperative industry/industry or government/industry efforts, and, perhaps most importantly, the willingness of companies (particularly end users) to invest their own capital in long-term development efforts. These factors are discussed further below.

Industry Structure

The most important U.S. participants in the advanced ceramics industry tend to be medium- or large-sized corporations that have experience with traditional ceramics or that are diversifying from other structural materials areas. These include Norton Co., Champion Spark Plug, Standard Oil Engineered Materials, Coors Ceramics, GTE, and Alcoa. The major U.S. companies that have structural ceramics products in production are listed in table 9-2. Most of these products are wear parts, refractories, cutting tools, or military items such as armor and radomes. Those companies that have major ongoing R&D efforts, but few if any commercial products are listed in table 9-3. New participants in the industry may

Table 9-2.—Major U.S. Companies With Structural Ceramics Products in Production, 1986

Company	Products
Advanced Refractories Technologies	Powders, nuclear products
Aluminum Co. of America	Powders, wear parts
Ceradyne	Armor, aerospace products, electronics
Champion Spark Plug Co.	Powders, insulators, jet igniters
Coors Ceramics Co.	refractory tubes, rods, electronics, wear parts
Corning Glass Works	Glass and glass/ceramics, aerospace windows, refractories
E.I. Du Pont de Nemours & Co.	Fibers
GTE Products Corp.	Wear parts, radomes, engine parts, electronics, Klystron and X-ray tubes
W.R. Grace & Co.	Grinding media, mill linings
Kennametal, Inc.	Cutting tools, wear parts, armor, gun parts
Norton Co.	Powders, bearings, filters, armor, cutting tools
Standard Oil Engineered Materials Co.	Refractories, heating elements, fibers, heat exchangers, wear parts
Solar Turbines, Inc.	Coatings, heat exchangers
3M Co.	Fibers
Union Carbide Corp.	Powders, coatings

SOURCE: Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," a contractor report prepared for OTA, Jan. 28, 1987.

Table 9-3.—Major U.S. Companies With Ongoing Structural Ceramics R&D Efforts, 1986 (little or no commercial production)

Company	R&D area
Aerospace Corp.	Space systems
Air Products and Chemicals, Inc.	Coatings
Astromet Associates	Refractories, wear parts, electronics, coatings
Avco Corp.	
Specialty Materials Division	Aerospace materials: heat shields, reentry systems
Brunswick Corp.	Radomes, missile systems
Cummins Engine Co.	Diesel engine parts
Ford Motor Co.	Diesel, turbine, and gas engine components; cutting tools
Garrett Corp.	
AiResearch Casting Co.	Turbomachinery
Garrett Turbine Engine Co.	Gas turbine engine components
General Motors Corp.	
Allison Gas Turbine Division	Gas turbine engine parts
Detroit Diesel Allison	Diesel engine parts
Howmet Turbine	Wear parts, specialty ceramics

SOURCE: Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," a contractor report prepared for OTA, Jan. 28, 1987.

come from chemical, petroleum, and other materials-based industries. Such companies, including Dow Chemical, Arco, Mobay, and Manville, already have experience with related processing technologies such as sintering, hot isostatic pressing, or sol-gel powder production methods.

In recent years, there has been a trend toward vertical integration from powder suppliers to finished components. Full vertical integration means the in-house capability to produce powders and process them into a finished product. A vertically integrated company has a high degree of control over all steps in the fabrication of the product, and it profits from sales of the higher value-added finished product. A vertically integrated ceramics supplier may hold an advantage over its more fragmented competitors in that an end user—e.g. an automobile company or a turbine producer—often prefers to obtain a complete system rather than obtaining all of the parts and assembling the product. This is particularly true of new materials used initially in low volumes.

In practice, there are few U.S. advanced materials companies that can be considered truly integrated. Alcoa has plans to move in that direction, and companies such as Corning Glass and Norton already have much of the required capability. Most U.S. ceramics companies are partially integrated; i.e., they perform some combination of powder production, design, assembly, machining, or testing in-house, but rely on outside sourcing for some essential functions. Examples include Cummins Engine Co., Kennemetal, Inc., and Solar Turbines, Inc.

Currently, there are no U.S. companies that could be considered horizontally integrated, i.e., that make a variety of products that use similar materials. Horizontally integrated companies have the capability of transferring knowledge and experience acquired in one ceramic application to another. An excellent example of a horizontally integrated company is the Japanese firm Kyocera, which is a world leader in electronic ceramics but also produces ceramic cutting tools, auto parts, and bearings. Kyocera also has a large subsidiary in the United States.

According to industry executives interviewed by OTA, it appears likely that there will be a restructuring of the U.S. ceramics industry over the next few years. There will probably be some new entrants, such as the chemical companies indicated above; however, overall it is expected that there will be a consolidation of efforts. This is likely to occur for two reasons. First, the small current markets for ceramics can support only a limited number of companies, and, given the technical and economic barriers that continue to plague structural ceramics, these markets are unlikely to expand rapidly in the next few years. Second, the complex technical requirements for successful participation in the industry necessitate a greater commitment of money, skilled personnel, and facilities than can be afforded by most firms.

Consolidation is likely to occur in the form of an increasing number of acquisitions, mergers, joint ventures, and other types of joint relationships. OTA found that 76 percent of the companies interviewed either were engaged in, or were seeking a joint venture.[4] A representative compilation of recent acquisitions, mergers, and joint ventures in the advanced ceramics industry is given in appendix 9-1 at the end of this chapter.

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[4] Business Communications Co., Inc., op. cit., 1987.

Foreign Participation in the U.S. Market

Foreign companies are positioning themselves to take a large part of the slowly developing U.S. market for structural ceramics. To date, there have been relatively few actual foreign acquisitions, although appendix 9-1 shows that joint ventures between foreign and U.S. ceramics companies are common, and several foreign companies are building plants in the United States. A compelling example of this trend is provided by the Japanese firm Kyocera. Kyocera's U.S. subsidiary is planning a large R&D center at its facility in Vancouver, Washington. Some of the best U.S. advanced ceramics scientists and engineers will be invited to do research there, where Kyocera will also provide condominium-style housing for the researchers and their families. Kyocera has also endowed ceramics professorships at the Massachusetts Institute of Technology, Case Western Reserve University, and the University of Washington.

Government/Industry Relationships

The U.S. Government spends $100 to $125 million annually on advanced ceramics R&D, more than any other country.[5] A breakout of Federal funding for structural ceramics in fiscal year 1987 is given in table 10 of chapter 2. In order of decreasing expenditure, the principal agencies funding structural ceramics R&D are the Department of Energy (DOE), Department of Defense (DoD), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and National Bureau of Standards (NBS), for a total of around $65 million in fiscal year 1987. A large proportion of this was spent for R&D performed within industrial laboratories; e.g., in fiscal year 1985, 57 percent of a total of $54.5 million went for work performed in industrial laboratories, 30 percent to Federal laboratories, 12 percent to universities, and 1 percent to non-profit laboratories.[6]

DOE laboratories such as Oak Ridge, Argonne, Los Alamos, Sandia, and Lawrence Berkeley have large ceramics programs and many industrial contractors. Major ongoing programs in ceramic technology development include DOE's Heat Engine Propulsion Program, administered by Oak Ridge National Laboratory. Fiscal year 1987 funding was $22.5 million, including $4.5 million for heavy-duty diesel transport, $8 million for advanced Stirling engine development, and $10 million for the Advanced Gas Turbine Program, which became the Advanced Turbine Technology Applications Program (ATTAP) in 1987. DOE is also funding the Advanced Heat Exchanger Program in its Office of Industrial Programs, at about $2 million in fiscal year 1987.[7]

As yet, DOE industrial contractors have not deemed it profitable to launch major efforts to commercialize products resulting from these programs. Program cost sharing by industry averages around 20 percent, which is enough to secure an exclusive license for the technology from the government.[8] Over 85 percent of the industry executives contacted by OTA felt that continued government support for the industry was necessary.

The United States Advanced Ceramics Association (USACA) has recently completed a survey that estimates annual U.S. industry investment in ceramics R&D at $153 million, some 20 percent higher than the Federal R&D figure.[9] This situation contrasts sharply with that prevailing in Japan, where industry is estimated to spend some four times more than the government for ceramics R&D.[10]

In recent years there has been growing State and regional funding for development of advanced ceramics. Several States, including New York, New Jersey, Ohio, and Pennsylvania, now fund centers of excellence in ceramics based at local universities, and some have initiated technology incubation programs designed to assist small start-up ceramics companies. The opportunities for government/university/industry collaboration in advanced materials R&D are discussed in greater detail in chapter 10.

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[5] John B. Wachtman, "U.S. Continues Strong Surge in Ceramic R&D," *Ceramic Industry*, September 1986.

[6] According to an unpublished survey performed by S.J. Dapkunas, National Bureau of Standards.

[7] According to presentation by Robert B. Schulz, Department of Energy, at the Interagency Coordinating Committee Meeting on Structural Ceramics, National Bureau of Standards, May 1987.

[8] Ibid.

[9] Steve Hellem, Executive Director, United States Advanced Ceramics Association, personal communication, November 1987.

[10] This estimate assumes that the Ministry of International Trade and Industry (MITI) figures for the industry/government investment ratio for all Japanese R&D holds true for advanced ceramics.

Industry Associations and Professional Societies

Industry associations and professional societies perform two important functions that enhance the competitive position of U.S. companies. First, they organize regular meetings that serve as forums for the exchange of new ideas. Second, they serve as points of aggregation for the needs and concerns of the affiliated companies, and they help to communicate these needs to government.

A variety of professional societies sponsor meetings and other activities relating to advanced ceramic materials, as do such government agencies as DOE, NASA, and DoD. These include the American Ceramic Society (ACerS), ASM International, the Federation of Materials Societies (FMS), and the American Institute of Chemical Engineers (AIChE).

In 1985, a trade association called the United States Advanced Ceramics Association (USACA) was formed to promote the interests of U.S. ceramics companies by gathering and disseminating information on worldwide ceramics activities, identifying opportunities and barriers to commercialization, and providing industry input to government on such issues as process patents, standards, and R&D policy. It is a national association representing more than 30 companies with an interest in the emerging field of advanced ceramics. USACA membership as of 1987 is given in table 9-4.

Table 9-4.—United States Advanced Ceramics Association Membership List, November 1987

Member Company
Air Products and Chemicals, Inc.
Allied-Signal Aerospace
Aluminum Company of America
AVX Corp.
Blasch Precision Ceramics, Inc.
Celanese Corp.
Ceradyne
Champion Spark Plug Co.
Chrysler Corp.
Coors Ceramics Co.
Corhart Refractories, Inc.
Corning Glass Works
Deere & Co.
Dow Chemical Co.
Dow Corning Co.
E.I. du Pont de Nemours & Co.
Electro-Science Laboratories, Inc.
Engelhard Corp.
Ferro Corp.
GA Technologies, Inc.
General Ceramics, Inc.
General Motors Corp.
GTE Products Corp.
Harshaw/Filtrol Partnership
IBM Corp.
Lanxide Corp.
Martin Marietta Corp.
Norton Co.
PPG Industries
Standard Oil Engineered Materials Co.
Sundstrand Corp.
The Titan Corp.
3M Co.
Union Carbide Corp.
W.R. Grace & Co.

SOURCE: United States Advanced Ceramics Association.

Japan

With limited metal and timber resources, Japan has historically placed a great emphasis on ceramics, which can be made from abundant raw materials. Japan has attained a leadership position in advanced ceramics through its eminence in the electronic ceramics market, including capacitors and substrates/packages, a business that was dominated by the United States just a decade ago. The assets, human resources, and experience gained through developing and manufacturing electronic ceramics have put Japanese companies in a strong position to develop advanced ceramics for structural applications.

Japan's commitment to ceramics technology has been highlighted recently.[11] Japanese Government and industry have long been very optimistic about the market potential for advanced ceramics. For example, a recent projection by the Ministry of International Trade and Industry (MITI) put the annual market for all advanced ceramics at $30 billion by the year 2000 in Japan alone.[12] Most estimates of the U.S. market in this time frame are one-third to one-half as large. Although MITI's estimate includes a wider spectrum of materials and products than most such estimates, it reflects the broad consensus within Japan that advanced ceramics is a key technology for the future.

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[11] National Materials Advisory Board, "High Technology Ceramics in Japan," NMAB-418, (Washington, DC: National Academy Press, 1984).

[12] *Materials and Processing Report*, Renee Ford (ed.), vol. 1, No. 5 (Cambridge, MA: MIT Press, August 1986).

Industry Structure

Many Japanese companies participate in the advanced ceramics industry, including roughly 100 powder suppliers, 250 suppliers of finished components, and 150 equipment suppliers. Recent entrants into this field include steel, cement, and petrochemical companies.

Major Japanese powder suppliers are listed in table 9-5. Many are vertically integrated, and also produce shapes. A prime example, Kyocera, manufactures shapes used in both electronic and structural applications from powders produced captively.

Leading manufacturers of finished ceramic components are listed in table 9-6. Kyocera, NGK Spark Plug, and Narumi China are leading producers. Japanese manufacturers of finished ceramic components tend to offer products to more than one end-use market; i.e., they are horizontally integrated.

A critical difference between Japan and the United States is the commitment of Japanese commercial end users to incorporate ceramics in current products. Examples are given in table 9-7. In most cases, this commitment is made in spite of the fact that the ceramic component is more expensive than the metal component it replaces. For instance, the production cost of the ceramic turbocharger rotor used in the Nissan Fairlady Z automobile is reportedly in the range of $60; by comparison, U.S. companies generally feel that costs must fall below $15 per rotor before production would be considered.

Foreign Participation in the Japanese Market

Traditionally, corporate acquisitions within Japan are rare. In fact, there is no simple way of saying "takeover" or "acquisition" in Japanese.

Table 9-5.—Major Japanese Powder Suppliers

Supplier	Oxides	Nitrides	Carbides	Other
Asahi Chemical	X			
Chichibu Cement	X[a]			
Daiichi Kigenso	X			
Denki Kagaku Kogyo		X	X	
Fuji Titanium				X
Hitachi				X
Hitachi Chemical Ceramics			X	
Hitachi Metals				X
Japan New Metals		X	X	
Kawasaki Steel	X			
Kyocera	X			X
Kyoritsu Ceramics	X	X	X	
Mitsubishi Chemical				X
Mitsubishi Mining & Cement	X			
Murata Manufacturing	X			
Nippon Kokan	X[a]	X[a]		
Nippon Steel	X[a]	X[a]	X[a]	X[a]
Shin Nippon Kinzoku Kagaku			X	
Shinagawa Refractories				X
Showa Aluminum	X			
Showa Denko	X[a]	X	X	
Sumitomo Chemical	X	X		
Sumitomo Electric	X	X[a]	X[a]	
Toray				X
Toyo Soda	X	X[b]		
Ube Industries	X		X[a]	

[a] Products are under development.

[b] Minor supplier of silicon nitride.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-6.—Major Japanese Manufacturers of Finished Ceramic Components

- Asahi Glass
- Asahi Optical
- Figaro Engineering
- Hitachi
- Hitachi Chemical Ceramics
- Hitachi Metals
- Koh'a China
- Koransha Insulators
- Kurosaki Refractories
- Kyocera
- Matsushita Electronic Components
- Mitsubishi Heavy industries
- Mitsubishi Metals
- NGK Insulators
- NGK Spark Plug
- Narumi China
- Nippon Denso
- Nippon Tungsten
- Noritake
- Shinagawa Refractories
- Showa Denko
- Sumitomo Electric
- Toshiba Ceramics
- Toshiba Tungaloy

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

The Japanese word for it, "nottori," also means "hijacking." Acquisition of a Japanese firm is considered humiliating for the firm's management. One exception is if a company wants to enter a business and it acquires a company with a declining market position.

Overall, the Japanese Government is gradually making it easier for foreign firms to invest in Japanese companies. However, this is a recent development. Although no official statistics are available, industry sources estimate that the number of investments by foreign firms in Japanese companies is less than a dozen per year in all industries.[13] Initially, foreign investors take a minority interest, with the intent of increasing their share over time.

Formation of joint ventures is increasing in popularity within the Japanese advanced ceramics industry. Although it is most common that both partners are Japanese, some U.S. industry sources believe that joint ventures represent the best means for foreign companies to participate in the Japanese market. Recently formed joint ventures—including some involving foreign corporations—are listed in Appendix 9-2.

Although not actually joint ventures, informal collaboration among Japanese companies to develop ceramic products is common, particularly in the automotive sector, as shown in table 9-8.

Licensing agreements involving ceramics companies are relatively uncommon in Japan. Those

Table 9-7.—Major Japanese Users of Ceramic Parts or Components

End user	Automotive	Aerospace	Biomedical	Other[a]
Toyota Motors	X[b]			
Nissan Motors	X			
Fuji Heavy Industries	X			
Matsuda Motors	X[c]			
Isuzu Motors	X[c]			
Mitsubishi Heavy Industries		X[b]		
Kawasaki Heavy Industries		X		
Showa Aircraft		X		
Mitsubishi Electric		X		X
Asahi Optical			X[b]	
Kyocera	X[b]		X[b]	X[b]
Koransha Insulators			X[b]	X[b]
Mitsubishi Mining & Cement			X[b]	X[b]
Toray				X[b]
Noritake				X[b]
ARS Edge				X[b]
Fujitsu				X
Toshiba				X[b]
Matsushita Electric Components				X[b]

[a] Includes electronics and wear parts.
[b] Manufactures ceramic components captively for these applications.
[c] Products under development.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

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[13] Strategic Analysis Inc., op. cit., 1987.

Table 9-8.—Collaborative Programs Between Japanese Automobile and Ceramics Companies

Automobile manufacturer	Ceramics company	Focus of program
Isuzu Motors	Kyocera	Diesel engine parts
Mitsubishi Motors	Asahi Glass	Auto parts
	NGK Insulators	Rocker arms
Nissan Motors	Hitachi Chemical	Turbocharger rotors
	NGK Spark Plug	Turbocharger rotors
	NGK Insulators	Turbocharger rotors
Toyota Motors	Toshiba	Engine parts

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

identified primarily involve the processing of raw materials. Some recent licensing agreements are included in appendix 9-2. Technology exchanges that are short of formal licensing agreements also exist between the following Japanese companies and foreign companies: Toshiba and Cummins Engine Co. (USA); NGK Insulators and Cummins; and NGK Spark Plug and ICI (UK).

Government/Industry Relationships

Japan has developed an international reputation for the close cooperation in technology development that exists among government, academia, economic institutions, and industry. From a U.S. perspective, the Japanese system contains several unusual features, including: scientific and technological competence at the highest levels of government and industry policymaking; a mechanism for developing a national consensus among government, industry, and academia as to technological goals; and a willingness of financial institutions and industries to cooperate with the government in achieving the consensus goals.

The role of the Japanese Government in advanced materials development has been reviewed recently.[14] [15] Figure 9-1 shows the relationships among the most important Japanese Government agencies responsible for science and technology policy. The three principal agencies involved in advanced ceramics R&D are MITI, the Science and Technology Agency (STA), and the Ministry of Education.

A breakdown of government funding for both structural and electronic advanced ceramics in 1983 and 1985 is presented in table 9-9. However, these data, like other funding data typically reported by the Japanese Government, include only the costs of resources and capital equipment; they omit overhead and salary expenses. Such basic expenses normally account for only about 20 percent of a typical U.S. government contract. Therefore, to compare these figures with similar U.S. figures, they should be scaled up by roughly a factor of five. According to the raw figures in table 9-9, MITI, STA, and the Ministry of Education all spent roughly comparable amounts for a total of about $20 million in 1985. That would scale up to about $100 million when salary and overhead expenses are added—roughly comparable to the estimates of $100-125 million in the United States.[16]

MITI reports that private and government funding sources provide 79 percent and 21 percent, respectively, of the expenses for all R&D in Japan. Although figures are not available for private sector ceramics R&D, industry sources report that the amount funded by private industry is much larger than that funded by government. Assuming that the ratio for all R&D holds for ceramics, this would put industry's investment level at about $400 million per year in Japan.

MITI's primary thrust in advanced materials is through its Agency of Industrial Science and Technology (AIST), which promotes industrial R&D to strengthen the country's mining and manufacturing industries. AIST oversees the opera-

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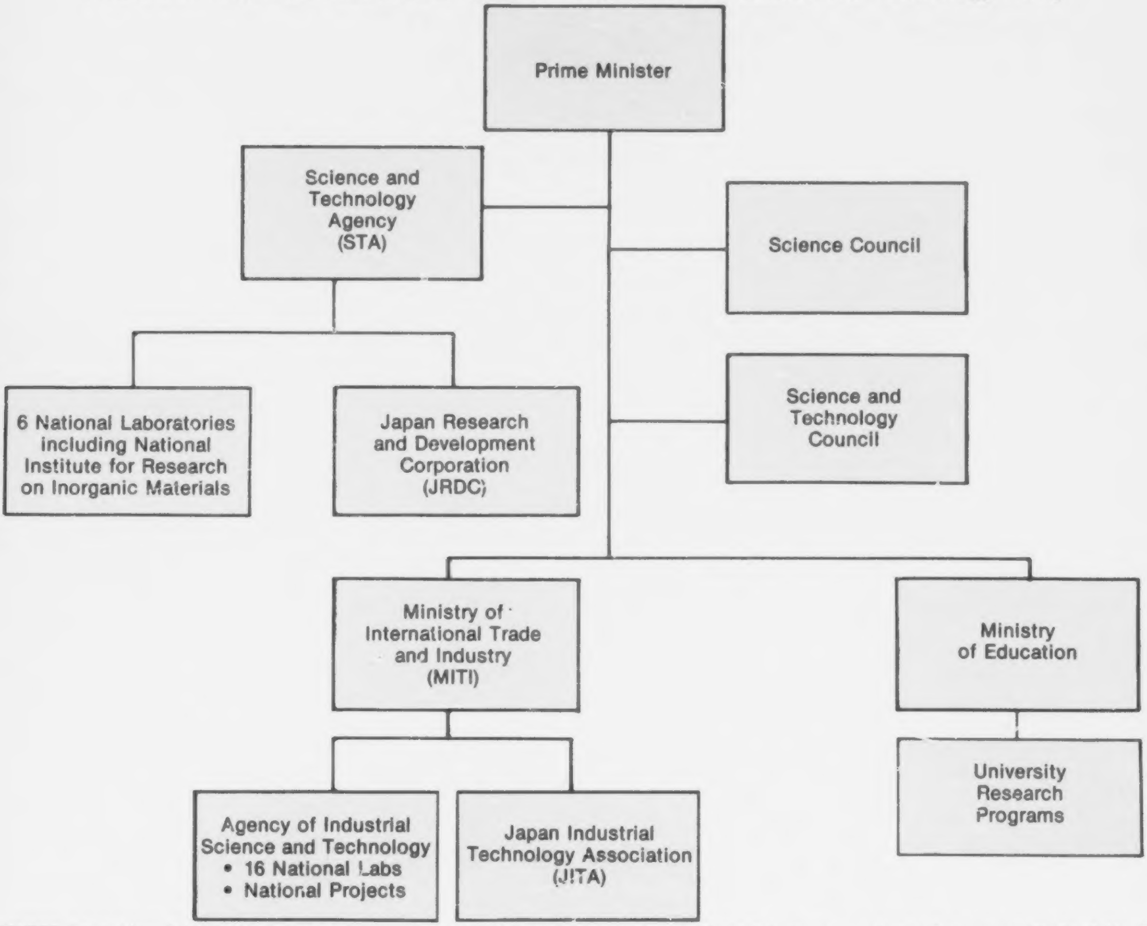
[14] National Materials Advisory Board, op. cit., 1984.

[15] "JTECH Panel Report on Advanced Materials in Japan," JTECH-TAR-8502, a contract study prepared for the National Science Foundation by Science Applications International Corp., May 1986.

[16] John B. Wachtman, op. cit., 1986.

Figure 9-1.—Japanese Government Agencies Responsible for Science and Technology Policy


Prime Minister
Science and Technology Agency (STA)
Science Council
6 National Laboratories including National Institute for Research on Inorganic Materials
Japan Research and Development Corporation (JRDC)
Science and Technology Council
Ministry of International Trade and Industry (MITI)
Ministry of Education
Agency of Industrial Science and Technology
• 16 National Labs
• National Projects
Japan Industrial Technology Association (JITA)
University Research Programs

SOURCE: Adapted from Science Applications International Corp., JTECH Panel Report on Advanced Materials in Japan, a contractor study prepared for the National Science Foundation, May 1986.

tions of 16 national laboratories, with an annual budget of $600 million in 1985. In 1981, MITI also initiated the R&D Project on Basic Technology for Future Industries, a 10-year, $32 million project to be carried out completely in private industry. This program involves extensive government/industry coordination and includes seven projects on advanced materials, among them one on ceramics.[17] In FY 1988, MITI is planning to initiate an 8-year joint R&D project with Toyota, Nissan, Mitsubishi, Kyocera, and Isuzu to develop a ceramic gas turbine engine. Development costs are expected to be 20 billion yen (about $138 million).[18] In addition, a 9-year, $105 million program, aimed at developing a stationary ceramic gas turbine for power generation, has also been requested to begin in fiscal year 1988.[19]

In addition to sponsoring ceramics R&D, MITI promotes the use of new ceramics technologies in industry. For instance, the Japan Industrial Technology Association (JITA), under MITI, promotes the transfer of technology from AIST laboratories to industry, and it serves as a clearing house for domestic and foreign technical infor-

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[17] National Materials Advisory Board, op. cit., 1984.

[18] "Deja Vu—Yet Again," *Forbes*, Nov. 16, 1987, p. 282.

[19] According to information provided by Robert B. Schulz, U.S. Department of Energy, November 1987.

Table 9-9.—Japanese Government Funding for Advanced Structural and Electronic Ceramics[a]

	Funding ($ million)[b]	
Government source	1983	1985
Ministry of International Trade and Industry:		
R&D Project on Basic Technology for Future Industries	3.2	3.5
National Laboratories	2.0	2.3
Agency of Natural Resources and Energy	0.0	0.8
Consumer Goods Industry Bureau	0.2	0.1
Other agencies	0.3	0.6
Science and Technology Agency:		
Research and Development Corp. of Japan	1.2	1.6
National Institute for Research On Inorganic Materials	8.0	8.8
Ministry of Education	1.5	1.6
Total	16.4	19.3

[a] Includes only costs of resources and capital equipment. Does not include overhead and salary expenses.
[b] Constant 1985 dollars. 1 US$ = 200 yen.
[c] Includes funds for all ceramics-related research, primarily advanced ceramics.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

mation. JITA also provides an advisory service on patents. Private organizations that have been set up to license AIST patents and technology are the Japan Patent Information Center (JAPATIC) and the Industrial Technology Promotion Association (ITPA), which are provided with the most promising government patents.

MITI's AIST also has control over disbursement of funds from the Japan Development Bank (JDB), a government financial institution that may make loans to ventures sanctioned by the government at rates lower than market rates. Such interlocking of government, industry, and financial institutions is a very important aspect of Japanese industrial policy.

The STA has responsibility for developing and implementing science policy directives received from the prime minister. These directives are based on recommendations from the Council on Science and Technology and the Science Council of Japan, a cabinet-level advisory group. STA administers six government laboratories, including the National Institute for Research on Inorganic Materials (NIRIM), a major center for ceramics research in Japan. NIRIM maintains an extensive visiting scientist program, to which researchers from universities and private industry are temporarily transferred by their home institutions.

Like MITI, STA promotes the use of advanced ceramics technologies in industry. For instance, STA's Japan Research and Development Corp. (JRDC), a nonprofit, quasi-governmental corporation patterned after the National Research and Development Corporation (NRDC) in the United Kingdom, is chartered to promote commercial exploitation of government and university research results. JRDC selects research results having good commercial potential and underwrites a large fraction of the selected private firm's development costs in the form of interest-free loans. These loans are not repaid if the venture is not successful. JRDC may also serve as a broker between a government inventor or researcher and a small company desiring to commercialize the invention or research result.

The Ministry of Education sponsors R&D activities at universities and attempts to facilitate cooperation among universities. Formal consulting arrangements between industry and university researchers are not permitted. However, interactions among industry, university, and national laboratories are facilitated by personnel exchange programs. It is common for senior visiting scientists from industry to spend 2 or more years in residence in university or government laboratories while on full salary from their permanent employers.[20]

Despite the careful attention to technology development and use embodied in the various government agencies and policies described above, it is important to stress that by far the greater burden of Japanese ceramics R&D is shouldered by industry. Japan has succeeded in developing a national consensus that ceramics technologies are the way of the future, and Japanese industry has made a long-term commitment to the commercialization of these technologies. Particularly significant is the commitment of end user companies, such as automobile companies, to incorporate ceramics in current products, even though it is not profitable to do so at present. For example, Toyota plans to produce an all-ceramic diesel engine with injection molded, sintered silicon nitride by 1991. It is anticipated that every part will be proof tested, suggesting that this production will be very labor intensive.[21] This "technology push" strategy contrasts sharply with the approach taken by U.S. end user companies, which are oriented toward return on investment in a 3- to 5-year time frame.

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[20] Robert J. Gottschall, "Basic Research in Ceramic and Semiconductor Science at Selected Japanese Laboratories," DOE/ER-0314, a trip report prepared for the U.S. Department of Energy, March 1987, p. 5.

Industry Associations

One recipient of MITI's funds is the Japan Fine Ceramics Association (JFCA), established in 1982. Regular members of JFCA include more than 170 suppliers of raw materials and finished components, as well as users of fine ceramics. JFCA's objective is to contribute to the development of the national economy by laying the foundation for the advanced ceramics industry through exchange of information, improvement and diffusion of technology, and diversification of applications.

A national institute associated with JFCA, called the Japan Fine Ceramics Center (JFCC), was established in Nagoya in May 1985. JFCC promotes relationships among universities, government agencies, and industries in Japan and throughout the world. It also integrates technical databases involving ceramics, provides technical know-how, and develops standard methods for testing and evaluating ceramics. Initially, the private sector contributed $40 million and local government contributed $15 million to fund the center.

Western Europe

Industry Structure

Alcoa and ESK are the two largest manufacturers of ceramic powders in Europe and account for about half of the European merchant market. Alcoa is the leading supplier of high-purity alumina; ESK is the leading supplier of various grades of silicon carbide. Some companies—including Philips, Siemens, Norton, and Magnesium Elektron—manufacture powders for captive consumption of ceramic parts, often electronic components. Manufacturers also import ceramic powders from Japan and the United States.

Overall, about 40 European companies manufacture ceramic parts for sale in the merchant market. Another dozen or so, mainly electronic companies, produce components for captive consumption. The 11 largest firms, listed in table 9-10, account for about 75 percent of the merchant market for ceramic parts, excluding imports.

A modest trend exists among powder suppliers to forward-integrate into the production of parts.

Table 9-10.—End-Use Markets Served by Major European Ceramics Suppliers in 1986

	End-Use Market			
Supplier	Automotive	Aerospace	Biomedical	Other[a]
Ceramiques et Composites (F)				X
Cookson (UK)				X
Desmarquest (F)	X	X		X
ESK (FRG)				X
Feldmuehle (FRG)	X		X	X
Friedrichsfeld (FRG)		X	X	X
Haldenwanger (FRG)				X
Hoechst-CeramTec (FRG)	X		X	X
Hutschenreuter (FRG)	X			
Norton,[b] (FRG)		X		X
Societe Europeene Propulsion (F)		X		X
Stettner (FRG)				X

[a]Includes electronic ceramics and other structural ceramics.
[b]U.S. firm with manufacturing operations in West Germany.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

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[21] Ibid.

However, most major producers of finished ceramic components are not backward-integrated into powders. A trend toward horizontal integration also exists. Horizontal integration is often achieved through acquisitions of existing suppliers. A number of European companies, including Bayer (FRG), Feldmuehle (FRG), and Hoechst (FRG), have recently acquired other ceramics businesses as part of a move toward horizontal integration.

Acquisitions, joint ventures, and licensing agreements involving ceramics have become somewhat more common in recent years among European firms (see app. 9-3). For instance, only one acquisition took place in 1982, whereas 7 took place in 1986. The product areas most often acquired were silicon carbide, silicon nitride, zirconia, and other oxides.

Like acquisitions, the number of joint ventures involving European ceramics companies has increased significantly in the past several years. Although most joint venture partners were already participating in the ceramics industry, many also were chemical companies, end users, or equipment suppliers. Almost half of joint ventures are targeted at the electronic ceramics industry. Some of the most important recent joint ventures are given in appendix 9-3.

Although licensing agreements involving ceramics are still relatively uncommon in Europe, they are increasing in popularity, as shown in appendix 9-3. Two companies, ASEA Cerama, a Swedish consortium, and Lucas-Cookson-Syalon, a British company, license ceramics technology as an integral part of their marketing strategies.

Foreign Participation in the European Market

Europe is now generally self-sufficient in key raw materials and finished ceramic parts. However, Japanese and U.S. suppliers still hold strong positions in certain product categories, as shown in table 9-11. For example, the North American suppliers Alcoa, Reynolds, and Alcan remain major suppliers of alumina. High-purity silicon nitrides from Japanese suppliers—especially Toyo Soda and Ube Industries—are increasingly penetrating the European market. Finished structural ceramic parts are generally supplied by European producers with little or no foreign participation, although U.S. and Japanese suppliers predominate in electronic ceramics.

The major Japanese and U.S. suppliers of powders and finished ceramics to Europe are listed in table 9-12. Most Japanese suppliers merely resell products through European sales offices. Although this is also a common marketing approach used by U.S. companies, several U.S. firms have also established manufacturing facilities in Europe.

European Community Programs

In the early 1980s, the European Community (EC) perceived a greater need for a planned research effort based on a common research policy among participating nations. The EC cited two reasons for this need. First, it was aware of a technology lag in many areas versus its U.S. and Japanese competitors. Second, the EC felt that the fragmented and overlapping research efforts of industrial countries could be unified and harmonized by the creation of a common research strategy.

The EC began funding research on ceramics around 1982. Since that time, the EC has funded research through the program on Technical Ceramics (1982-85), the Basic Research in Industrial Technologies for Europe (BRITE) Program (1985-88) and the European Research in Advanced Materials (EURAM) Program (1986-89). In these programs, proposals were requested in targeted areas. The EC is rapidly increasing research and development funding for ceramic programs. From negligible involvement in 1982, the EC spent about $4 million through 1985. About $20 million is committed for ceramic projects in the BRITE and EURAM programs.[22]

In the EC's second Framework Program on Science and Technology (1987-91), with a total approved budget of $5.4 billion, the budget line for science and technology of all advanced materials is expected to be about $220 million.[23] EC

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[22] According to information supplied by Wim van Deelen, Delegation of the Commission of the European Communities, Washington, DC, August 1987.

[23] Ibid.

Table 9-11.—Impact of Foreign Suppliers on the Western European Advanced Ceramics Market

Product	Dominant source		
	Europe	United States	Japan
Powders:			
Oxides:			
Alumina	X	X	
Zirconia	X		
Rare earths	X		
Carbides	X		
Nitrides	X		X
Titanates[a]		X	
Titanium diboride	X		
Finished parts:			
Automotive	X		
Aerospace	X	X	
Biomedical	X		
Electronics		X	X

[a] Primarily barium and strontium.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-12.—Major Japanese and U.S. Suppliers of Powders and Finished Ceramics to Western Europe

Company	Product		Business activity		
	Powders	Finished products	Manufacturing	Sales	JV
Japanese:					
Figaro Engineering		X		X	
Kyocera		X		X	X
Matsushita Electronic Components		X		X	
Murata Manufacturing		X	X		
Narumi China		X		X	
Showa Denko	X			X	
Toyo Soda	X			X	
Ube Industries	X			X	
U.S.:					
Alcoa	X		X		
AVX		X	X		
Brush-Wellman		X		X	
Cabot		X		X	X
Ceradyne		X		X	
Coors Ceramics		X	X		
Duramic	X			X	
GTE Sylvania	X		X		
Norton		X	X		
SOHIO Engineered Materials		X		X	
TAM	X			X	

Business activity code:
Manufacturing = European manufacturing operation
Sales = Sales network only
JV = Joint venture program with Western European company.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

funding for ceramics research goes to numerous enterprises and research organizations throughout the Community.

National Programs[24]

European government spending on national R&D programs for advanced ceramics is collectively estimated at about $220 million in 1985, as summarized in table 9-13. Recipients of these funds included research centers, universities, and private industry. West Germany, France, and the United Kingdom accounted for about 85 percent of the total. The following are some brief examples of national programs.

West Germany.—Total government funding for advanced ceramics R&D is estimated at about $75 million in 1985. The Ministry for Research and Technology (BMFT) has launched a 10-year, $440 million research program for new materials, including high-temperature metals, new polymers, powder metallurgy, and ceramics. West Germany is considered to be the European leader in structural ceramics, with over 50 companies actively involved; leading companies are Feldmuehle, Friedrichsfeld, and ESK.

Table 9-13.—European Government Spending on National R&D Programs for Ceramics in 1985[a]

Country	Government Expenditures ($ million)
West Germany	75
France	64
United Kingdom	51
Sweden	7
Netherlands	4
Italy	6
Belgium	5[b]
Finland	5
Other[c]	3
Total	$220

[a] Includes government funding for materials, office expenses (such as salaries), facilities, research centers, universities, and private industry.
[b] Includes Neoceram capital of $4 million (see text).
[c] Includes Denmark, Ireland, Norway, and Switzerland.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-14.—French Government Funding for Ceramics Research, 1985

Organization	Funding ($ million)	Percent of total
National Center for Scientific Research (CNRS)	$20.0	31
Commission on Atomic Energy (CEA)	13.1	20
Ministry of Defense	9.5	15
Ministry of Research and Technology	7.7	12
Ministry of Education	6.2	10
Other	7.5	12
Total	$64.0	100

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

France.—The French Government provided $64 million for advanced ceramics research in 1985, as broken out in table 9-14. About 30 percent of the research was carried out in the National Center for Scientific Research (CNRS) in Meudon. French companies have developed a strong position in ceramic composite technology.

United Kingdom.—Annual government spending for ceramics is estimated at $51 million. The United Kingdom has two major ceramics programs underway: Ceramic Applications for Reciprocating Engines (CARE), and Advanced Ceramics for Turbines (ACT). These are jointly funded by government and industry at a level of about $9 million over four years.

Sweden.—Swedish Government spending on advanced ceramics in 1985 is estimated at around $7 million. A significant fraction of Swedish ceramics research is carried out at the Swedish Silicate Research Institute (SSRI) in Goteborg, which is sponsored by some 30 Swedish companies. In 1986, the Institute operated on a budget of about $1 million and was engaged in cooperative work with Chalmers University of Technology (also in Goteborg) and the Japanese Government Industrial Research Institutes (GIRI) in Nagoya and Kyushu. SSRI and GIRI formed a 3-year cooperative research program involving silicon nitride and sialon.

The leading Swedish ceramics corporation is ASEA Cerama, a 1982 joint venture of six Swedish companies, which was formed to promote applications of ceramic parts made by hot isostatic pressing (HIP). ASEA is the world leader in HIP equipment and technology.

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[24] Budget figures in this section are drawn from Strategic Analysis, Inc., op. cit., 1987, unless otherwise specified.

Netherlands.—Research funding for advanced ceramics by the Dutch government dates from 1983 when, with support from the Department of Industry, a task force of scientists and industry representatives created the Innovation-Oriented Research Program—Technical Ceramics (IOP-TK). In 1984, 14 projects were selected in ceramic powder production and fabrication technologies, and in 1985 the IOP-TK was funded at about $9 million over 8 years. Presently, about $4.1 million has been approved over the next 4 years for 10 projects.

Italy.—The Italian Government is reportedly in the process of approving a $50 million program for advanced materials, of which about $25 million is scheduled to be reserved for advanced ceramics.

Belgium.—Government-sponsored R&D in advanced ceramics is estimated at about $1.5 million annually, mainly administered by the Institute for the Encouragement of Scientific Research in Industry and Agriculture (IRSIA). The regional Walloon government has recently donated $4 million in starting capital for Neoceram, a joint venture of five Belgian partners.

POLYMER MATRIX COMPOSITES

Advanced polymer matrix composites (PMCs)—often referred to simply as advanced composites—are usually defined as those composites reinforced with continuous fibers having properties comparable to S-glass (high-stiffness glass) or better, and using resins with properties comparable to epoxies or better. Usually excluded are E-glass-reinforced polyester or vinylester matrices, which constitute over 85 percent of all PMCs, as indicated in chapter 3.[25] Advanced composites are the topic of this section.

The advanced composites industry can be conceptualized as having four distinct levels, as indicated in figure 9-2. These are: producers of basic materials such as resins and fibers; prepreggers; shapes producers; and end users. At the primary level are firms producing the polymer resins for the matrix and fibers for reinforcement. Resins, as unformulated monomers, and fibers, in the form of yarn or fabric, are purchased by manufacturers of prepregs. Prepreggers typically formulate a resin system and combine it with various reinforcing fibers to produce prepregs in the form of woven fabric, unidirectional tape, and filament tow. Prepregs are the principal starting materials in fabricating composite structures. The merchant market for prepregs is large and fairly well-defined. Shapes or structures are the next level of the composite industry. Fabricated composite shapes may be made captively for incorporation into other products, or sold on the merchant market to end users in various industries.

The United States is the largest producer and consumer of advanced composites in the world. Much of the pioneering work on these materials was conducted in the United States, and domestic suppliers rank among the most important companies in the worldwide business. In 1985, the total value of advanced composites structures produced in the United States, Western Europe, and Japan was approximately $2 billion. Of this, the United States alone accounted for nearly two-thirds, as shown in table 9-15. European production was less than half this size, although it was similar to the U.S. in its emphasis on aerospace end uses. Japan ranked a distant third in overall production, with the orientation of its advanced composites industry toward the recreational market. The relative composition of these three markets is broken out by end use in table 9-16.

United States

Industry Structure

The structure of the U.S. advanced composites industry is largely a result of its orientation toward aerospace applications. Segmentation has

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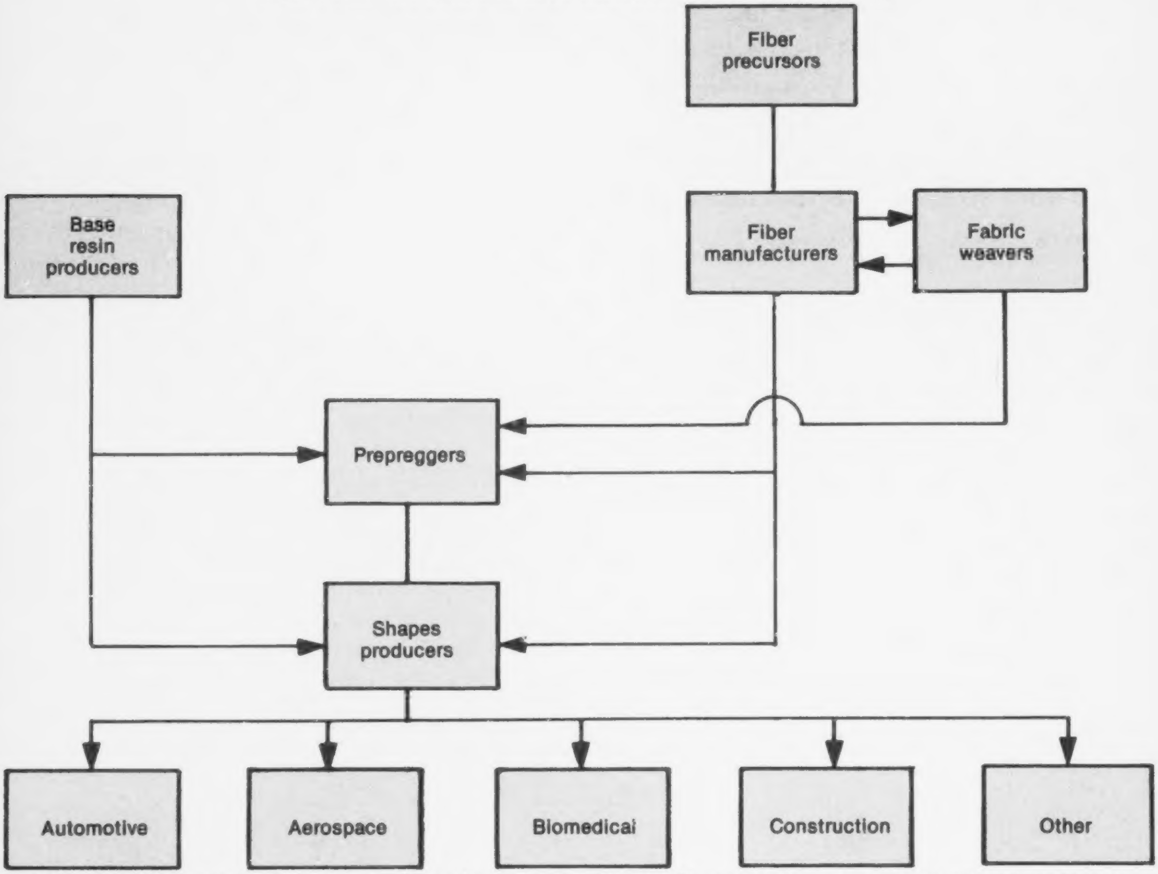
[25] However, due to their lower cost, E-glass composites are the most likely materials to be used in automotive body structures, as indicated in ch. 7. Given the sophisticated design and manufacturing processes, as well as the high strength and reliability required in automotive structural applications, it would seem appropriate to include such PMCs in the category of advanced composites.

Figure 9-2.—Structure of the Advanced Composites Industry



The advanced composites industry has four primary levels: resin and fiber producers; prepreggers; shapes producers; and end users.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-15.—Production Value of Advanced Composite Structures, 1985

Regional market	Sales ($ millions)[a]	Percent of total
United States	$1,350	64
Western Europe	550	26
Japan	200	10
Total	$2,100	100

[a]Value of finished structures.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

largely occurred along product lines (fibers, resins, prepregs, and shapes). Other important industry characteristics include limited production volumes and a cost structure commensurate with the high value of the end uses.

Hercules, Hexcel, Fiberite, and Boeing are the most important companies in the U.S. composites industry. All possess a strong orientation toward the aerospace industry, the largest and most technology-driven market segment. The U.S. market for finished composite structures in 1985 was valued at approximately $1.4 billion, of which about half was consumed by the aerospace industry, as indicated in table 9-16.

The structure of the advanced composites industry is fairly complex, with significant overlap among the activities of individual firms. Companies such as Hercules, for instance, produce carbon fiber, prepregs, and finished shapes for the merchant market, and use them captively as well.

Table 9-16.—Breakdown of Regional Markets for Advanced Composites by End Use, 1986

Region	End use percentage[a] Aerospace	Industrial[b]	Recreational
United States	50	25	25
Western Europe	56	26	18
Japan	10	35	55

[a] Based on value of fabricated components.

[b] Includes automotive, medical, machinery, and non-aerospace defense applications.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

End users such as Boeing captively produce composite shapes from prepregs and use them in commercial and military aircraft. The business activities of key participants in the U.S. advanced composites industry in 1986 are summarized in table 9-17.

The following is a discussion of key companies in the various levels of the advanced composites industry, including market share and extent of vertical integration

Resin Suppliers.—The suppliers of resins for advanced composites are mainly large, diversified chemical and industrial product manufacturers that produce large quantities of plastics for a variety of end-use markets. Unformulated resins going to the advanced composites market are specialty products that typically account for only a small amount of each supplier's resin sales.

Ciba-Geigy, Shell, and Dow Chemical control almost two-thirds of the U.S. resin market for advanced composites. These three suppliers are epoxy producers that dominate resin sales for all applications worldwide. Leading suppliers of thermoplastic resins are ICI, Amoco, and Phillips. A list of the most important suppliers of base resins by product type is shown in table 9-18.

Fiber Suppliers.—U.S. consumption of fibers for advanced composites totaled over 7 million pounds in 1985. Graphite fibers alone accounted for nearly half of the total amount by weight, and almost two-thirds of the dollar value. Aramid fibers ranked second, with over 20 percent of the weight and value. S-2 glass fibers accounted for 25 percent of the total consumption by weight, but only 10 percent of the total value. The re-

Table 9-17.—Participation of Key Firms in the U.S. Advanced Composites Industry, 1986

Company	Advanced material product[a] Base resins	Fibers	Prepregs	Shapes
American Cyanamid			X	
Amoco Performance Products	X	X	m	m
Avco		m	m	X
BASF		X	X	m
Boeing				X
Ciba-Geigy	X		X	m
Dow Chemical	X			
Du Pont	X	X	m	m
Ferro			X	
Grumman				X
Hercules		X	X	X
Hexcel			X	m
HITCO		m	X	X
Hysol Grafil		X	m	m
ICI	X			
ICI Fiberite			X	
Lockheed				X
LTV				X
McDonnell Douglas				X
Northrop				X
Phillips 66	X		m	m
Rohr Industries			X	
Shell Chemical	X			
United Technologies				X

[a] X = major product; m = minor product.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-18.—Major Suppliers of Base Resins for Advanced Composites in the United States, 1986

Type of resin	Supplier
Bismaleimide	Celanese Ciba-Geigy Dow Chemical
Epoxy	Celanese Ciba-Geigy Dow Chemical Shell
Phenolic	Monsanto Reichhold
Polyester	Ashland Freeman PPG Reichhold
Polyether sulfone (PES)	ICI
Polyetheretherketone (PEEK)	ICI
Polyimide	Du Pont
Polyphenylene sulfide (PPS)	Phillips
Poly (amide-imide)	Amoco
Vinylester	Ashland Dow Chemical Reichhold

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-19.—Major Fiber Suppliers in the United States, 1986

Aramid	Du Pont
Boron	Avco
Carbon (PAN)[a]	Amoco Avco BASF Fiber Materials Great Lakes Carbon Hercules HITCO Hysol-Grafil Stackpole
Carbon (Pitch)	Amoco Ashland
Carbon (Rayon)	Amoco HITCO Polycarbon
Glass	Owens-Corning

[a] PAN = polyacrylonitrile precursor.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

maining volume was made up of specialized fibers, such as boron, ceramic, and other polymers, which collectively accounted for only about 1 percent of the total weight of fiber reinforcements.

Nine firms supply carbon fiber for advanced polymer composites in the United States, as indicated in table 9-19. The top three suppliers, Hercules, Amoco, and BASF, together account for approximately 85 percent of the total market. Hercules remains the largest supplier with a market share of over one-third. Amoco, which acquired the carbon fiber business of Union Carbide in 1986, is the second largest firm. Amoco is currently the only U.S. company capable of producing the important polyacrylonitrile (PAN) precursor for carbon fiber production; currently, 100 percent of PAN fiber precursor used by the military is imported from Japan and the United Kingdom. Amoco is currently in the process of qualifying its PAN-based fibers for military use. The third largest firm supplying carbon fiber is BASF, a West German company that purchased the Celion carbon fiber business from Celanese. Despite worldwide overcapacity for carbon fiber, DoD's interest in securing stable domestic sources of both fiber and PAN precursor has prompted the planning of new facilities in the United States.

Du Pont is currently the only U.S. producer of aramid fibers. In addition, through its acquisition of Exxon's Materials Division, Du Pont is making preliminary moves toward supplying pitch-based carbon fibers as well. Owens-Corning Fiberglas is the only U.S. producer of high-performance glass for composites. A number of other firms, including Avco, Fiber Materials, and Hysol-Grafil, also produce various other fibers for reinforcement.

Prepreg Suppliers.—U.S. consumption of advanced composites prepregs totaled over 3,000 metric tons in 1985. High-performance graphite fiber prepregs accounted for about 40 percent of total use, followed by glass fiber prepregs with slightly over 30 percent. Aramid fiber-based prepregs contributed an additional 27 percent of total consumption, with the remainder made up of specialty prepregs of boron, quartz, or other fibers.

Overall, it is estimated that more than 80 percent of U.S. sales of prepregs are to the merchant market. Few major shapes producers, such as large aerospace firms, have perceived sufficient benefits to warrant internal manufacture of prepregs.

Suppliers of prepregs are generally large, diversified chemical and industrial product manufacturers that have developed technology and expertise in advanced composites. Eight suppliers account for approximately 90 percent of the market. The three largest firms—Fiberite, Hercules, and Hexcel—together account for about two-thirds of merchant prepreg sales, followed by Ciba-Geigy, Narmco, HITCO, American Cyanamid, and Ferro.

Shape Suppliers and End Users.—Roughly estimated, the U.S. market for aerospace composite structures was valued at about $650 million in 1985. The majority, about 60 percent, of composite shapes were manufactured captively by the major U.S. aircraft firms and prime military contractors. The remaining 40 percent was divided among a number of large and small subcontractors that produce parts for merchant sale.

Outsourcing for composite shapes tends to be more common among manufacturers of civilian aircraft. Major airframe producers such as Boeing rely heavily on merchant fabricators or subcontractors to fabricate composite forms. In many cases, outsourcing for composite parts relates to larger marketing factors, particularly promoting foreign sales of finished aircraft to countries where subcontractors operate. As a result of such "offset" agreements, subcontractors in Japan (Fuji), Spain (CASA), and Italy (Aeritalia) are among those exporting major quantities of fabricated aircraft structures to the United States.

Captive fabrication tends to occur more frequently among the major military contractors. Firms such as McDonnell-Douglas, General Dynamics, Grumman, and Northrop, for instance, are virtually self-sufficient in supplying their own composites needs. In addition, LTV, Grumman, and Northrop also fabricate structures for other firms.

Integration.—Greater consolidation and increased integration have been market characteristics of the U.S. advanced composites industry over the past few years. In some respects, the poor financial performance of the industry as a whole has played a part in both trends. Many of the advantages of forward integration relate to lower raw material costs and better coordination of technologies across product categories. Perhaps the greatest single motivation for this tendency is the desire to move into more profitable product categories. The carbon fiber business, for instance, has demonstrated poor financial performance compared with either prepregs or fabrication.

Of the three areas, fabrication of composite structures provides the greatest returns in the advanced composite industry. Examples of recent moves toward forward integration among U.S.-based suppliers are shown in table 9-20. Hercules, perhaps the most significant player in the market, is vertically integrated from raw materials to final shapes. The firm has long had a competitive advantage in the carbon fiber business due to its position as an important military contractor and merchant composite fabricator. Rival suppliers, BASF and Amoco, have no such reliable market to support their carbon fiber operations.

Recently, Boeing Technologies created a stir in the industry by announcing an agreement with Nikkiso (Japan) to license production technology for carbon fiber. While Boeing has a pilot plant under construction, few in the industry believe this move signals Boeing's intentions to eliminate outsourcing of raw materials. Boeing contends that the agreement is nothing more than an outgrowth of the company's longstanding interest in internal materials research.

Acquisitions.—Since 1984, there have been an increasing number of significant acquisitions and consolidations within the advanced composites industry. Some of the more notable are listed in Appendix 9-4. To a large extent, these acquisitions embody a growing investment in compos-

Table 9-20.—Recent Moves Toward Forward Integration Among U.S.-Based Advanced Composites Suppliers

	Manufacturing capability	
Company	Original position	Integration
Amoco	Resins, fibers	Prepregs
Du Pont	Fibers	Prepregs, shapes
Phillips	Resins, prepregs	Shapes

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

ites by large, diversified chemical and industrial firms. Overall, the composites industry has not proven to be very profitable for its participants. The industry's greatest returns are thought to lie in the long term as truly large volume applications are commercialized. Acquisitions represent a long-range investment that is most easily made by larger, diversified companies.

Joint Ventures.—The rationale for joint ventures among firms in the advanced composites industry is heavily influenced by issues of marketing and technology. In the case of marketing, joint ventures have provided a means for U.S. firms to assume a local identity when participating in foreign markets.

In the case of technology, the joint venture is intended to provide technological synergies between firms with different strengths. Hercules, for instance, recently teamed with biomedical implant maker Biomet to develop and market orthopedic implants. Hysol-Grafil was formed with the intention of mating Courtaulds' experience in carbon fibers with Dexter's resin technology. In appendix 9-4 are listed recent joint ventures among firms in the advanced composites industry.

Licensing Agreements.—The licensing of basic technology from foreign firms has been a characteristic of the U.S. composite industry since its inception. The basic process for the production of carbon fibers was imported by major U.S. producers from firms such as Toho Rayon, Toray, and Courtaulds. Two of these licensing agreements remain in effect. In other areas, licensing is an important mechanism for the transfer of production and distribution rights for finished products both into and outside of the United States. Appendix 9-4 gives some of the more prominent licensing agreements in effect today.

Foreign Participation in the U.S. Market

The advanced composites industry has become a more international business and one less dominated by U.S. firms. The past several years have seen a dramatic increase in the activity of European firms in the United States. Courtaulds, BASF, ICI, and Ciba-Geigy, for instance, now rank among the major participants in the U.S. market as a result of joint venture and acquisition activity. In terms of market share, foreign-owned materials firms now control 25 percent of the U.S. resin market, 50 percent of prepreg sales, and over 20 percent of the carbon fiber market. The foreign share of the finished structure business is much smaller.

Several motivations appear to be behind the increased involvement of foreign firms in the U.S. market. The most obvious is that the U.S. market is the largest such market in the world, and is likely to grow rapidly, particularly on the military side. As military use grows, so will the emphasis on U.S.-based suppliers. Many of the acquisitions of U.S. firms by large European conglomerates are evidence of a faith in the long-term viability of the industry by those with sufficient resources to ride out the current lean times.

The transfer of technology from U.S. operations back to Europe is also an incentive for foreign participation. In many ways, the European composites market can be viewed as a smaller version of the U.S. market. A strong defense and aerospace orientation is coupled with an equally strong emphasis on local sourcing for raw materials and prepregs. The growth of the European commercial aircraft industry and the potential for channeling composite technology into the automotive industry are also important considerations.

Although Japanese fiber manufacturers hold some of the best production technology for carbon fiber in the world, the activity of Japanese firms in the U.S. has been largely confined to licensing and technology agreements with U.S. firms. The provisions of these agreements have severely limited direct Japanese participation in the U.S. market. As a result, two of the world's largest carbon fiber producers, Toray and Toho Rayon, currently have a very minor role in the largest market for fibers. This situation leads many U.S. observers to suggest that the Japanese will be forced to reassess their posture toward the United States in the near future.

Sources in the U.S. industry point out that the absence of Japanese suppliers from the U.S. market is a major disadvantage for Japanese firms because of their lack of proximity to important technological developments. With leading-edge research in advanced composites oriented toward military applications, Japanese fiber firms are several steps removed from key technological trends and in serious danger of losing their leadership position in fiber technology. This condition is worsened by the absence of any significant Japanese market for military or aerospace products.

There are vague indications of how Japanese participation is likely to change in the future. Some speculate that to support massive investments in technology and productive capacity at home, Japanese firms will break prior agreements and begin selling carbon fiber directly in the United States. In this case, it is envisioned that the Japanese may team with one or more of the major prepreggers that lack captive fiber technology. A second scenario holds that the Japanese will follow the lead of many European firms by acquiring a U.S. firm. In this case, a likely target would be one of the few remaining independent prepreg firms.

In the longer term, there are predictions that other Asian countries, such as South Korea, may become active in furnishing fiber to the U.S. market. Such countries are envisioned as competing directly with the Japanese in supplying inexpensive, lower performance fibers for cost-sensitive applications such as the automotive or construction industries.

Government/Industry Relationships

Historically, the U.S. advanced composites industry has been driven by DoD, particularly for aircraft and space applications. To a great extent, this remains true today. DoD sponsored over 70 percent of Federal PMC R&D in 1986 (see ch. 3), and this proportion is expected to increase in the future, fueled by the need for lighter, stronger materials for new weapons systems such as the Advanced Tactical Fighter, the Strategic Defense Initiative, the Stealth bomber, and the LHX helicopter. In addition, use of composites is expected to expand in military ground vehicles, surface ships, and submarines.

Consistent with the industry's military orientation, most of the policy issues of greatest concern to the industry revolve around defense-related regulations and policies, such as export controls on composite products and technology, domestic sourcing of key raw materials, and military procurement programs (see ch. 11).

Industry Associations and Professional Societies

A variety of professional societies and organizations conduct meetings on advanced composites and support the industry. These include the Society of the Plastics Industry (SPI), the Society for the Advancement of Materials Processes and Engineering (SAMPE), ASM International, and the Society of Automotive Engineers (SAE). Recently, a trade association called the Suppliers of Advanced Composite Materials Association (SACMA) was formed to address common concerns of composites suppliers. A list of SACMA members is given in table 9-21. SACMA has been

Table 9-21.—Members of the Suppliers of Advanced Composite Materials Association (SACMA)

Member Company
Allied Corp.
American Cyanamid Co.
Amoco Performance Products
Asahi Nippon Carbon Fiber Co.
Ashland Petroleum Co.
Celion Carbon Fibers
Ciba-Geigy Corp.
Dow Chemical
Dow Corning Corp.
E.I. Du Pont de Nemours & Co.
Enka America
Ferro Corp.
Fortafil Fibers, Inc.
Hercules, Inc.
Hexcel Corp.
Hysol Grafil Co.
ICI Fiberite
Mitsubishi Rayon America
Narmco Materials
Phillips 66 Co.
Rhone-Poulenc, Inc.
RK Carbon Fibers
Shell Chemical Co.
Teijin America, Inc.
Textile Products, Inc.
3M Co.
Toho Rayon Co.
Toray Industries
TPC (Unit of BASF)
U.S. Polymeric, Inc.
Xerkon Co.

SOURCE: Suppliers of Advanced Composite Materials Association.

active in addressing health issues, standardization of composites, export controls, and domestic sourcing requirements of DoD. Consistent with the defense/aerospace orientation of the composites industry today, SACMA is primarily concerned with the defense market, and members consider commercial markets, such as automotive, to be of secondary importance.

Japan

The Japanese advanced composites industry was initiated to supply the aircraft and space industries of the United States. Since that time, however, most of the Japanese domestic growth has been in the recreational markets. This emphasis differs greatly from the U.S. market, which is primarily oriented toward defense applications. The composition of the Japanese advanced composites market is currently 55 percent recreational, 35 percent industrial, and 10 percent aerospace (see table 9-16).

Unlike many end uses, the recreation industry frequently accepts higher cost and higher quality materials because the customer is willing to pay a premium for these products. However, Japan is already starting to lose its market share in advanced composites for sporting goods to South Korea.[26]

Industry Structure

Resin Suppliers.—In Japan, most suppliers of base resins for advanced composites are leading chemical companies. Resins for advanced composites comprise a small fraction of total production. Yuka Shell Epoxy, Mitsui Petrochemical, and Asahi Chemical together hold about 70 percent of the Japanese market for resins used in advanced composites. These manufacturers produce epoxy, the principal matrix material. A list of selected suppliers of base resins by product type is given in table 9-22.

Table 9-22.—Major Suppliers of Base Resins for Advanced Composites in Japan

Resin type	Supplier
Bismaleimide-triazine polyimide	Mitsubishi Chemical (Amoco)[a] Mitsubishi Gas Chemical Nippon Polyimide (Rhone-Poulenc-Mitsui Petrochemical)[b] Toray
Epoxy	Asahi-Ciba (Asahi Chemical-Ciba-Geigy)[b] Mitsui Petrochemical Sumitomo Chemical Yuka Shell Epoxy
Polyamide	Asahi Chemical Mitsubishi Chemical Toray
Polyester	Dai Nippon Mitsui Toatsu Sumitomo Chemical
Polyether sulfone (PES)	ICI Mitsui Toatsu (ICI)[a] Sumitomo Chemical (ICI)[a]
Polyetheretherketone (PEEK)	ICI Mitsui Toatsu (ICI)[a] Sumitomo Chemical (ICI)[a]
Polyphenylene sulfide (PPS)	Kureha Chemical Tohto Kasei Toray-Phillips[b] Toso Susteel
Vinylester phenol	Dow Chemical

[a]Resin produced by company in parenthesis and marketed by the Japanese company.
[b]Joint venture partners.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Fiber Suppliers.—Japanese consumption of fibers for advanced composites totaled over 2 million pounds in 1985. Graphite fibers accounted for about two-thirds of domestic consumption. Aramid fibers were second, with over one-quarter of the total weight. The remaining volume, less than 10 percent of the total, was made up of specialized fibers, including glass, boron, ceramics, and miscellaneous others. Selected Japanese suppliers of fibers for advanced composites are given in table 9-23.

Five Japanese firms supply carbon fibers, and six supply carbon fiber precursor (PAN). Together, the top two suppliers, Toray and Toho Rayon, account for 80 percent of the total production. The percentage of export production for both companies is as high as 60 percent or more. Toho Rayon exports large quantities of precursor to firms in the United States, while Toray has

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[26] Presentation by R.A. Fasth, Kline & Co., "Advanced Polymer Composites: The Challenges for the Future," at the Conference on Emerging Technologies in Materials, sponsored by the American Institute of Chemical Engineers, Minneapolis, MN, Aug. 18-20, 1987.

Table 9-23.—Major Fiber Suppliers in Japan, 1986

Fiber type	Supplier
Alumina	Sumika-Hercules
Aramid	Toray Teijin
Boron	Vacuum Metallurgical
Carbon,[a]	Toray Toho Rayon Asahi Nippon Carbon Mitsubishi Rayon Nikkiso
Carbon[b]	Kureha Chemical Mitsubishi Chemical
Ceramic[c]	Ube
Glass	Nittobo
PAN precursor	Sumika-Hercules
Polyethylene	Mitsui
Silicon Carbide	Nippon Carbon

[a] PAN-based (PAN = polyacrylonitrile).
[b] Pitch-based.
[c] Ceramic fiber consisting of titanium, silicon carbide, and oxygen.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

licensed precursor technology to Amoco. Toho Rayon also exports carbon fiber to Southeast Asian countries, including Taiwan and Hong Kong, for sporting goods applications. The position of leader between the two firms frequently alternates whenever one firm expands its production facilities. Toray also supplies aramid fibers, which are imported into Japan through Du Pont-Toray.

Prepreg Suppliers.—In Japan, fiber manufacturers or their affiliates generally produce prepregs for fabricating advanced composites, and all current carbon fiber manufacturers sell prepregs as well as carbon fiber. Sakai Composite and Toho Rayon are the largest prepreggers, followed by Asahi Composite and Mitsubishi Rayon. Sakai Composite, a subsidiary of Toray, manufactures prepregs mainly for sporting good applications. The ranking of prepreggers is roughly the same as that of fiber suppliers because they manufacture prepregs using their own materials. Unlike carbon fiber manufacturers, which are largely Japanese entities (with the principal exception of Sumika-Hercules), many of the prepreg and shapes suppliers in Japan are joint ventures with foreign firms. They include Asahi Composites, Kasei Fiberite, Dia-HITCO Composites, and Toho Badische. The activities of the most important prepreggers are given in table 9-24.

Kasei-Fiberite is a joint venture between Mitsubishi Chemical and Fiberite. Mitsubishi Chemical has begun to produce pitch-based carbon fibers from which it plans to manufacture prepregs. These pitch-based carbon fibers are not the general purpose types that Kureha Chemical manufactures; rather, they are high-strength fibers whose specifications are comparable to PAN-based carbon fiber.

A very important development in the composites business will be the commercialization of low-cost, pitch-based carbon fibers. Many sources in both Japan and the United States expect the availability of these low-cost fibers to accelerate the use of composites in cost-sensitive applications such as automobiles and construction. Pitch fiber-reinforced concrete has already been used for curtain walls in buildings in Tokyo.[27] This material is lighter and tougher than

Table 9-24.—Participation of Major Prepreg Suppliers in the Japanese Market, 1986

	Business activity			
Supplier	Resins	Fibers	Prepregs	Shapes
Asahi Composite			X	X
Hitachi Chemical			X	X
Kasei Fiberite			X	X
Mitsubishi Rayon		X	X	X
Nitto Electric			X	X
Sakai Composite (Toray)	X[a]	X[a]	X	X[a]
Somar			X	X
Sumika-Hercules			X	X
Toho Rayon		X	X	X

[a] Produced by Toray.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advancod Materials," a contractor report prepared for OTA, Mar. 24, 1987.

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[27] "Panels Use Carbon Fibers," *Engineering News Record*, Aug. 1, 1985.

ordinary concrete, permitting the use of less structural steel and lower construction costs.

Shape Suppliers and End Users.—Japanese companies that manufacture finished composite components include Fuji Heavy Industries, Mitsubishi Heavy Industries, Kawasaki Heavy Industries, Nikkiso, and Tenryu Kogyo in the aerospace sector, and Somar and Nitto Electric in the recreation industry. End users with a major demand for composite structures in the recreation industry are R.K. Mizuno and Nippon Gakki (Yamaha); those in the automotive industry are Toyota and Nissan. Major end users for advanced composites in these and other fields are shown in table 9-25.

Foreign Participation in the Japanese Market

There are not many foreign manufacturers that have penetrated the Japanese advanced composites market. All of those that have succeeded have done so by establishing joint ventures with Japanese companies, such as Sumika-Hercules, Asahi Composite (Asahi Chemical and Ciba-Geigy), and Kasei Fiberite. Recent joint ventures are given in appendix 9-5. As indicated above, joint ventures are particularly common among prepreggers and shape fabricators.

Companies that recently formed licensing agreements with Japanese companies are shown in appendix 9-5. Many of these involve raw materials manufacture in which Japanese companies have supplied carbon fiber production technology to composites firms around the world.

Government/Industry Relationships

In contrast to the situation with ceramics, in which the names and budgets of the relevant agencies are well known, Japanese Government support for composites research is fragmented and difficult to identify. One of the few exceptions is MITI's budget for the R&D Project on Basic Technology for Future Industries, a 10 year, $32 million project initiated in 1981. The research topics in this project include both composites and ceramics. Total government expenditures dedicated to PMCs under the project were $3.2 million in 1983 and $3.6 million in 1985. This program places greatest emphasis on the aerospace and automotive applications of advanced composites.

Table 9-25.—Major End Users of Advanced Composites in Japan, 1986

Company	Recreational	Automotive	Aircraft/Aerospace	Medical	Construction	Other
Daiwa Seiko	X					
Shimano	X					
Olympic	X					
Ryobi	X					
R.K. Mizuno	X					
Honma	X					
Nippon Gakki	X					
Toyota Motors		X				
Nissan Motors		X	X			
Matsuda Motors		X				
Fuji Heavy Industries			X			
Mitsubishi Heavy Industries			X			
Kawasaki Heavy Industries			X			
Showa Aircraft			X			
Mitsubishi Electric			X	X		
Power Reactor & Nuclear Fuel Development						X
Mitsutoyo Manufacturing						X
Sankyo Seiki Manufacturing						X
Shimazu				X		
Toshiba				X		
Japan Medico				X		
Mitsui Construction					X	X

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Other executive branch organizations coordinating research on advanced composites are the Japan Research and Development Corp. (part of STA), the Consumer Goods Industry Bureau (part of MITI), the Agency of Industrial Science and Technology (MITI), the Science and Technology Council, and the Science Council.

The major national laboratories conducting advanced composites research are given in table 9-26. Government-supported research at universities is funded through the Ministry of Education. Total support for advanced composites R&D in the Ministry of Education accounted for less than $1 million in 1985.

At present, the National Space Development Agency of Japan, Mitsubishi Electric, Nippon Electric, and Mitsubishi Heavy Industries are working on the R&D of composite materials for aerospace end uses. Most Japanese companies and MITI consider automotive applications for advanced composites to have the best prospects for near-term development, while aerospace applications are viewed as long term. Obstacles to penetration of the worldwide aerospace market include a small domestic market, which is dominated by government-related projects, and the inaccessibility of the U.S. and European markets to Japanese suppliers. However, some analysts expect Japan to have an increasing presence in world aerospace markets as a result of joint ventures with Boeing, as on the 7J7 airplane.[28]

Table 9-26.—Major National Laboratories Performing Advanced Composites Research in Japan[a]

National Research Institute for Metals (STA)
National Aerospace Laboratory (STA)
Mechanical Engineering Laboratory (MITI)
National Chemical Laboratory for Industry (MITI)
Research Institute for Polymers and Textiles (MITI)
Industrial Products Research Institute (MITI)
Government Industrial Research Institute, Osaka (MITI)

[a] Laboratories under administration of Science and Technology Agency (STA) and Ministry of International Trade and Industry (MITI).

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Western Europe

The PMC business in Western Europe is concentrated in four countries: France, the United Kingdom, West Germany, and Italy. Together, these countries account for about 90 percent of the business, as shown in table 9-27. France dominates the advanced composites business in Western Europe, with a 55 percent share of sales. The substantial involvement of the French Government in the major aerospace, automotive, and energy-producing companies makes the French industry by far the most heavily state-subsidized one in Western Europe.

According to industry estimates, total production of advanced composites in Western Europe in 1985 was about 2,500 tons of product, worth about $550 million. This excludes imports from the United States. Significant amounts of advanced composites products are fabricated in the United States and exported to Europe either for assembly of European aircraft or for production of components for U.S. aircraft. For example, British Aerospace and McDonnell-Douglas are jointly producing the Harrier (AV-8B), and many of the composite components are manufactured in the United States. In addition, Aeritalia is manufacturing components for the Boeing 757 and 767. Prepregs are supplied from the United States for fabrication in Western Europe. If imports were added to the 2,500 tons, then total consumption in Western Europe would be twice this figure in 1985.

As in the United States, the aerospace and defense industries are the most important consumers of high-performance composites in Western Europe and are expected to continue to

Table 9-27.—Distribution of the Advanced Composites Business in Western Europe, 1986

Country	Percent of total
France	55%
United Kingdom	15
Germany	10
Italy	10
All others	10
Total	100%

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

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[28] Robert Poe, "Can Japan Launch a Commercial Aircraft Industry?" *High Technology*, March 1987, p. 42.

dominate in the future. Overall, the pattern of Western European consumption of composites is similar to that found in the United States, as shown in table 9-16.

Industry Structure

Resin Suppliers.—Large, multinational chemical companies dominate the supply of high-performance thermosets and thermoplastics to the European market. The major suppliers of epoxies include Shell, Ciba-Geigy, and Dow Chemical. Ciba-Geigy alone holds over half the market. Table 9-28 lists the major resin suppliers.

Fiber Suppliers.—The most important suppliers of high-performance fibers in Western Europe are shown in table 9-29. They include Hysol Grafil, a joint venture between Dexter (USA) and Courtaulds (UK); Soficar, a joint venture between Elf Aquitaine (F) and Toray (J); and Enka (NL). Total capacity for the production of carbon fibers in Europe is estimated at over 1,100 tons. The capacity in the United Kingdom is the largest, followed by Germany and France.

Production of aramid fibers recently commenced in Europe with the commissioning of Enka's new 5,000-ton plant in the Netherlands. In addition, Du Pont is building a plant in Northern Ireland to serve the Western European aramid fiber market.

Prepreg Suppliers.—Western European production of prepregs is concentrated in France, the United Kingdom, and Belgium. Significant quantities are also imported from the United States from companies such as Fiberite and Hercules. Overall, four suppliers (Ciba-Geigy, American Cyanamid, Hexcel, and Krempel) control about three-quarters of European prepreg production. A list of leading prepreggers and weavers is given in table 9-30.

In addition to these companies, a number of aerospace companies manufacture their own prepregs in-house. These include firms such as Aerospatiale (F), Airbus Industrie, and British Aerospace (UK).

Shape Suppliers and End Users.—Many of the leading aerospace companies manufacture finished components captively. These include British Aerospace, Fokker (NL), Messerschmitt-Boelkow-Blohm (FRG), Dornier (FRG), Aeritalia (I), Airbus Industrie, Agusta Group (I), Aerospatiale (F), and Dassault (F). The most important consumer of advanced composites in the aerospace field is Airbus Industrie, which is using substantial amounts of carbon fibers and epoxy resins for the Airbus 300 and 310. Other important civil aircraft programs under way at present in Western Europe include Fokker (model F100) and British Aerospace (models 125 and 146). Compared

Table 9-28.—Major Suppliers of Resins in Western Europe, 1986

Company	Location	Resin	Comment
Thermosets:			
Shell	UK	Epoxies	
Ciba-Geigy	SWI	Epoxies	Dominant supplier for composites
Dow Chemical	SWI	Epoxies	Ranks second as supplier to this sector
Thermoplastics:			
ICI	UK	Polyetheretherketone Polyether sulfone	
Phillips	B	Polyphenylene sulfide	Imports from U.S.
Amoco	SWI	Polyamideimide Polyetherimide	Imports from U.S.
BASF	FRG	Polysulfone Polyether sulfone	
General Electric	NL	Polyetherimide	Imports from U.S.
Bayer	FRG	Polyester (thermoplastic)	
Other:			
Rhone-Poulenc	F	Polyimides	Leader in development of polyimide technology
Technochemie	FRG	Bismaleimide	Owned by Boots Pharmaceuticals

KEY: B = Belgium; F = France, FRG = West Germany; NL = Netherlands; SWI = Switzerland; UK = United Kingdom.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-29.—Major Suppliers of High-Performance Fibers in Western Europe, 1986

Company	Plant location	Capacity (tons)	Comment
Carbon fibers:			
Hysol Grafil	UK	400	20%/80% joint venture between Dexter and Courtaulds
Soficar	F	300	65%/35% joint venture between Elf Aquitaine and Toray
RK Carbon Fibers	UK	150	Majority share owned by major textile company, Coats Paton
Enka (Akzo)	FRG	350	Based on Toho Rayon technology
Sigri	FRG	50	Investment in plant was $25 million Part of major carbon products company
Aramid fibers:			
Enka (Akzo)	NL	5,000	50%/50% joint venture with Dutch State Development Company
Du Pont	IR	7,000	Currently building plant
Glass fibers:			
Vetrotex	F	—	Division of St. Gobain Only European producer of R-glass
Other fibers:			
Societe Nationale des Poudres et Explosifs	F	1-2	Boron fiber producer owned by French Government
Bekaert NV	B	—	Stainless steel fibers

KEY: B = Belgium; F = France, FRG = West Germany; IR = Ireland; NL = Netherlands; = United Kingdom.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table 9-30.—Major Prepreggers and Weavers in Western Europe

Company	Location	Activity		Comment
		Prepreg	Weaver	
American Cyanamid	UK	X	—	
BASF	FRG	X		New facility based on Narmco U.S. plant technology
Bristol Advanced Composites	UK	X	X	Owned by BP Group
Ciba-Geigy				
Bonded Structures	UK	X		Leader in honeycomb structures
Brochier et Fils	F	X	X	Largest weaver of carbon fibers
Fiberite Europe	FRG	X		Part of ICI Group
Fibre & Mica	F	X		Narmco (BASF) licensee in France Owned by government company, Alsthom-Atlantique
Fothergill & Harvey	UK		X	Leading company in advanced materials, Owned by Courtaulds
Gividi	I		X	Leading weaver in Italy
Hexcel	B	X		Leader in honeycomb
Stevens-Genen	F	X	X	A leading weaver in Europe, turnover of $25 million in 1985
Interglas-Textil	FRG		X	One of largest weavers in West Germany
Krempel	FRG	X		Leading German prepregger
LNP (ICI)	NL	X		Leading producer of carbon fiber-reinforced nylon
Sigri	FRG		X	Leading weaver of carbon fibers
Specmat	UK	X		Leader in thermoplastic composites; part of N.R. Smith Engineering Group
Ten Cate Glas	NL	X	X	Part of Nyverdal Ten Cate, large textile group

KEY: B = Belgium; F = France, FRG = West Germany; I = Italy; NL = Netherlands; UK = United Kingdom.
SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

with the United States, however, the monetary value of advanced composites used in military aircraft in Western Europe is rather limited.

The recreation market represents the second most important market for advanced composites in Western Europe, accounting for about 18 percent of the total value of fabricated parts. The largest component of this group includes tennis rackets produced by such companies as Donnay (B), Dunlop Sports (UK), Snauwaert (B), and Fischer Ski (A).

The automotive sector ranks third after aerospace and recreation markets. About 60 percent of the advanced composites used in this sector go into specialty racing or other high-performance vehicles. In conventional automobiles, three sectors are under study for the use of composites: drive shafts, suspension systems, and engine components. GKN, a leading British company in automotive components, has recently marketed a glass fiber/epoxy leaf spring. Automotive companies with composite development programs under way include Renault, Ford, Porsche, and Audi.

Many consider Western Europe to lead the world in the biomedical applications of advanced composites. While not fully commercialized, composite joints, usually hip prostheses, are nearing the clinical stage in humans. Leading work in this area is being performed by Schunk und Ebe (FRG), Fothergill and Harvey (UK), and the University of Karlsruhe (FRG).

Integration.—As in the United States, most of the major end users of advanced composites in Europe are also important fabricators of finished components. Among material suppliers, there is evidence of a shift toward higher value-added products such as prepregs and shapes. Courtaulds, among others, has realized that to participate profitably in the advanced composites business in the long term, it must be more than a carbon fiber supplier. Therefore, the company is aggressively attempting to move downstream into the manufacture of components.

Given the limited number of independent prepreggers and component producers in Western Europe, the opportunities for resin producers and other fiber suppliers to forward integrate through acquisition are limited. Major resin suppliers such as ICI, Philips, and Akzo are increasingly emphasizing internal integration into thermoplastic composite products to broaden their participation in the business.

At present, most of the major aerospace companies manufacture advanced composite components for internal use. Prepregs are supplied externally. This is not expected to change in the future, since these companies possess the technology and the resources to continue their leadership in the manufacturing of components.

Acquisition activity in Western Europe typically has involved the absorption of smaller firms by major firms, as shown in appendix 9-6. Major acquisitions by European companies have tended to occur outside the continent, particularly in the United States.

Joint venture and licensing activities are typified by the importation of foreign technology into the European market. Recent joint ventures and licensing agreements are shown in appendix 9-6.

Foreign Participation in the European Market

Numerous U.S.-based companies participate either directly or indirectly in the advanced composites business of Western Europe. Among the more prominent is Hexcel, which has manufacturing facilities in France. Most of the other major participants, such as American Cyanamid, HITCO, and Dexter Hysol operate through joint venture companies. Other leading U.S.-based companies such as Hercules, Fiberite, and Narmco presently sell through sales organizations established in the major countries.

The major Japanese influence in the Western European market is in the fiber sector. Teijin is selling aramid fibers in Europe, while Toho Rayon and Toray have either licensed technology to European companies or have established joint ventures in the carbon fiber sector.

Currently, the only areas in which U.S.-owned companies hold major positions are aramid fibers and prepregs. Considering only U.S.-owned subsidiaries, the U.S. share of the European market is roughly estimated at 25 to 30 percent of European production. In the long term, the transfer of U.S. technology to Europe resulting from recent acquisitions in the United States is expected to make the European market even more self-sufficient.

Government/Industry Relationships

The following is a discussion of government/industry relationships in the European Community, as well as advanced composites programs in the leading countries: France, the United Kingdom, and West Germany.

European Community Programs

Two programs of the EC, BRITE and EURAM, sponsor research on advanced materials and their production technology. These programs address themselves to metals, ceramics, polymers and composites; in BRITE the emphasis is primarily on production technology. Ten out of 95 ongoing BRITE projects deal with composite materials.

Outside of the EC framework is the European collaborative program called EUREKA. EUREKA was created at the European technology conference held in Paris on July 17, 1985. To date, 19 European countries, as well as the Commission of the European Communities, are participating in the initiative. The objective of EUREKA is to improve the productivity and competitiveness of Europe's industries and national economies through closer cooperation among enterprises and research institutes in high technology.

At conferences in Hanover and London, 72 cooperative proposals were adopted as projects. To implement these projects, which cover a wide range of technologies, about $3.2 billion will be needed over a period lasting from 2 to 10 years. Although the technological areas covered by EUREKA and EURAM are closely related, the emphasis differs. EUREKA is primarily concerned with developing products, processes, and services having a market potential. Since these projects are closer to the market and involve less risk and uncertainty, financing is provided jointly by governments and private companies. However, financing arrangements vary greatly from one country and project to another.

In EUREKA, projects come directly from companies without reference to a strategic program within the EC. The direct agreement reached on a project by a number of firms is then presented to the EUREKA member States, which check that it is consistent with EUREKA's general principles and conditions for eligibility. Project management, including monitoring and evaluation of research, is done by the participating companies themselves.

Two EUREKA programs were approved in June 1986 that are related to advanced materials. The first, Carmat 2000, with proposed funding of $60 million for 4 years, involves evaluating PMCs for automobile structures. This program has 13 participants: eight organizations in France, three in West Germany, and one each in the United Kingdom and the Netherlands. The participants are listed in table 9-31. Peugeot, the principal coordinator, will work with the suppliers in developing a car with much greater use of plastics than today's automobiles. The objective of Carmat 2000 is to introduce a medium-sized car in 1990 at a lower cost by incorporating large amounts of engineering plastics and composites.

National governments will fund the project costs for Carmat 2000 up to a maximum of 50

Table 9-31.—Carmat 2000 Participants

- France
  - Peugeot
  - Usinor
  - Facilor
  - Ecole des Mines (Paris)
  - Cetim
  - St. Gobain
  - Elf Aquitaine
  - Inrets
- West Germany
  - Bayer
  - BASF
  - Battenfeld
- United Kingdom
  - ICI
- Netherlands
  - DSM

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

percent of the total. The participating companies and organizations will contribute the balance. Research responsibilities are divided among the participants. For instance, DSM is responsible for developing the bumper system, front subframe, rear wheel arches, trunk floor, and integrated plastic fuel tank. ICI is responsible for the doors and trunk lid, as well as the glazing; Bayer and BASF will be contributing their expertise in polymers and composites.

No information was available on the composites component of the second EUREKA program, called Light Materials for Transport Systems, other than that proposed funding is $15 million over 4 years.

National Programs

In addition to EUREKA and the EC-sponsored programs on advanced composites, various programs are underway in several countries.

France.—According to French Government sources, government support for all advanced materials research, including ceramics and composites, was $150 million in 1985. The most important institutes, universities, and companies involved in advanced composites R&D are given in table 9-32. Many of the French companies making major investments in advanced composites are government-owned. One government-owned company, Aerospatiale, the most prominent aerospace company in France, spent $60 to 80 million on R&D for developing composite structures in 1985.

United Kingdom.—To date, most of the government programs have been sponsored by the Ministry of Defence and are primarily aimed at the aerospace field. The government spent over $255 million in a 50-50 cost-sharing program with industry to research a new fighter aircraft in the Experimental Aircraft Program (EAP). The program was launched in 1983 to investigate technologies applicable to future fighter projects. It was designed to improve the capabilities of the British aerospace industry across a wide range of technologies, including carbon fiber composite structures.

Table 9-32.—Major French Laboratories Conducting Advanced Composites R&D, 1986

Public laboratories	Location
Ecole d'Application des Hauts Polymerés	Strasbourg
Ecole des Mines de Saint-Etienne	Saint-Etienne
Ecole Nationale Supérieure de Mécanique	Nantes
Ecole Supérieure de Physique Chimie Industrielle	Paris
Institute Nationale des Recherches de la Chimie Appliquées (IRCHA)	Paris
Institute Nationale des Sciences Appliquées	Villeurbanne
Laboratoire Nationale d'Essais	Trappes
Office Nationale d'Etudes et des Recherches Aerospatiales (ONERA)	Chatillon
Université de Besancon	Besancon
Université de Bordeaux	Talance
Université de Technologie de Compiégne	Compiegne
Université Pierre et Marie Curie	Paris
Université Scientifique et Technique de Lille Flandres Artois	Villeuneuve
Industry/private laboratories	Location
Aerospatiale	Paris
Alsthom Atlantique	Villeurbanne
Centre d'Etudes des Industries Mecaniques (CETIM)	Senlis
Charbonnages de France	Paris
Elf Aquitaine	Artix
Groupement d'Intéret Economique Régienov	Boulogne
Laboratoire de Recherche et de Controle du Caoutchouc et des Plastiques	Vitry
Matra	Paris
Métravib	Ecully
P.S.A.	Audicourt
Péchiney	Paris
Société Nationale des Poudres et Explosifs	Paris
Unirec	Firminy
Vetrotex Saint-Gobain	Chambery

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987; and Dominique Cotto, Science Attache, Embassy of France, personal communication, November 1987.

Many of the technologies developed for the EAP could be used on the planned European Fighter Aircraft (EFA), scheduled to enter service in the mid-1990s. Development of the EFA, one of the largest new military aircraft programs, will be undertaken by a consortium of companies from the United Kingdom, West Germany, Italy, and Spain. The United Kingdom and West Germany will have 33 percent of the consortium, Italy, 21 percent, and Spain, 13 percent. The EFA is expected to require considerable quantities of advanced composites.

Next to the Ministry of Defence, the Department of Trade and Industry (DTI) provides the most funding for composites R&D. In 1985, the DTI funded $14 million in PMC R&D, compared with less than $2 million in 1980. Also in 1985, DTI recommended a 5-year program for the development and exploitation of new materials and processes, including plastics, composites, and ceramics. The Materials Advisory Group of DTI recommended that the government should provide half of the funds for the program. Total government funding of this program is recommended at $170 million. Some of the most important organizations in the United Kingdom with research programs in advanced composites are given in table 9-33.

West Germany.—The West German Government has become much more active in providing funds for new materials research. In late 1985, the Ministry for Research and Technology announced that it would spend $440 million over a 10-year period, 1986-95, for materials research in the following fields: ceramics, polymers, composite materials, and high-temperature polymers and metals. The funds will be allocated on a project basis to companies, universities, technical institutes, or trade research organizations that have viable research programs that meet the department's guidelines. The government will provide up to 50 percent of the funding on the projects, with the research performing organizations providing the balance.

Table 9-33.—British Government Organizations With Research Programs in Advanced Composites, 1986

Organization	Location	Comment
Atomic Energy Research Establishment	Harwell	Has composites and polymers group that makes prepregs and components for merchant sale
Royal Aircraft Establishment	Farnborough	Quasi-government agency conducting research on advanced composites for aerospace sector
Experimental Aircraft Program	London	Partially government-funded development program with British Aerospace/Rolls Royce; total funds: $255 million

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

METAL MATRIX COMPOSITES

Like PMCs and CMCs, metal matrix composites (MMCs) utilize a variety of matrices and reinforcements, depending on the performance requirements of particular applications (see ch. 4). Aluminum is currently the most common matrix material, and the most common reinforcements are carbon/graphite, boron, and silicon carbide. Like PMCs, MMC development has been driven by military funding, and current demand for MMC materials in the United States is almost exclusively defense-oriented. High manufacturing costs continue to be a major barrier to the use of fiber-reinforced MMCs in commercial applications; however, particulate-reinforced MMCs, which exhibit moderate strength and stiffness improvements compared to the matrix alone, can be produced at a cost approaching that of conventional metals.

Following is a brief discussion of MMC-related activities in the United States, Japan, and Western Europe. Market information is omitted because data were not available for this assessment.

United States

Industry Structure

Presently, suppliers of MMC materials in the United States are small, undercapitalized companies with limited technical resources. This is because the current market is not large enough to attract large companies. In fact, several experts have characterized the industry as a "cottage" industry. R&D programs have been initiated by larger firms, including major aluminum suppliers such as Alcoa and Alcan. However, the companies actually supplying MMC materials, structural shapes, and components to the industry are either small, entrepreneurial firms or small subdivisions or subsidiaries of large corporations. Integration of these smaller producers into concerns having greater capital and R&D resources is considered an important step in the diffusion of the technology into commercial applications. The primary suppliers of matrix, reinforcement, and finished MMC materials in the United States are given in table 9-34.

At present, the fabrication capabilities of most MMC users are limited to secondary methods, such as machining. These users generally buy MMCs from suppliers in the form of billets, plates, structural shapes, or finished parts. However, a few end users are developing in-house casting, forging, and extrusion capabilities for MMCs. Examples include manufacturers of automotive components (such as diesel engine pistons and connecting rods) and several defense aerospace contractors.

Joint venture and acquisition activity in the industry is increasing. DWA Composite Specialties, for instance, has entered into a joint venture with Revmaster Aviation to produce silicon carbide- and boron carbide-reinforced aluminum alloys for automotive engine parts at a cost of $7 to $12 per pound.[29] Pistons, connecting rods, and rocker arms are under consideration. DWA also licensed ceramic particulate-reinforced aluminum technology to Alcoa in 1984.

Table 9-34.—Major Suppliers of MMC Materials in the United States, 1986

- Matrix
  - Alcan
  - Alcoa
  - AMAX
  - Avco/Textron
  - Dow Chemical
- Particulates
  - Norton
  - Standard Oil Engineered Materials
- Whiskers
  - Arco Chemical
  - American Matrix
  - J.M. Huber
  - Versar Manufacturing
- Fibers[a]
  - American Cyanamid
  - Avco/Textron
  - Du Pont
  - Standard Oil Engineered Materials
- Composites
  - Advanced Composite Materials
  - Amercom
  - Arco Chemcial
  - Avco/Textron
  - Cordec
  - Dural Aluminum Composites
  - DWA Composite Specialties
  - Materials Concepts
  - Novamet
  - Sparta

[a] See tables 9-19 and 9-23 for suppliers of graphite fibers, which are also used in MMCs.

SOURCE: Compiled by Office of Technology Assessment.

Recently, several important companies have been put up for sale. Arco Silag has been sold by Horsehead Industries to Tateho America; Amercom, Inc., is being acquired by Atlantic Research Corp.; and Textron has placed its Avco Specialty Materials Division up for sale.[30]

Alcan established Dural Aluminum Composites, which it acquired from SAIC. Dural has produced some 20,000 pounds of silicon carbide-reinforced aluminum and has sent it to 65 corporations and laboratories for evaluation.[31] Alcoa is developing its ARALL composite (a laminate of aluminum and aramid fibers bonded with epoxy). However, the Alcoa effort is still in the developmental stage, and materials are not being offered for sale commercially.

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[29] Dural Aluminum Composites has quoted prices as low as $3 per pound in commercial quantities.

[30] Joe Dolowy, President, DWA Composite Specialties, Inc., personal communication, November 1987.

Lockheed-Georgia, which began work on MMCs in 1980, is working with Arco Chemical Co. and Avco Specialty Materials Division to develop silicon carbide-reinforced aluminum containing whiskers or fibers as reinforcement. This Lockheed group uses a spray process to make silicon carbide fiber-reinforced aluminum composites for use in-house. This work is aimed at developing material for fins to be used on the next generation of the Air Force's Advanced Tactical Fighter. Lockheed-Georgia will design, manufacture, and test two fighter-type vertical fins made from each MMC material for a program sponsored by the Air Force.

Government/Industry Relationships

The greatest interest in MMCs has been for defense and space applications. Accordingly, most of the funding for development of the MMC industry has come from DoD ($154.5 million between 1979 and 1986) and, to a much lesser extent, NASA ($9.1 million between 1979 and 1986).[32] Other agency contributions are negligible. DoD funding of MMCs over the same period is considerably less than that spent on PMCs ($327.7 million).[33]

There has been little government funding of MMCs for commercial applications in the United States. Until very recently, companies have shown little interest in developing MMCs for use in commercial applications. Diffusion of MMC technology from military to commercial uses is hindered not only by high costs but also by national security restrictions placed on the dissemination of technical data and export restrictions imposed by the Departments of Commerce, State, and Defense. (These restrictions, which have been very confusing to MMC supplier companies, are discussed in greater detail in ch. 11).

Japan

Industry Structure

The principal companies supplying MMCs in Japan are the traditional metals suppliers and suppliers of fibers and particulates for PMCs and CMCs. These include Toho Rayon, Toray, Mitsubishi Aluminum, Kobe Steel, and Nippon Steel. Major organizations involved with MMC materials in Japan are listed in table 9-35. Companies experimenting with MMC products include Hitachi, Ishikawajima-Harima Heavy Industries, Honda, and Toyota.

The MMC industry in Japan differs significantly from that in Western Europe and the United States, in that the same companies that are involved with ceramics and PMCs also produce MMCs. The end user industries in Japan that are interested in MMCs are the automotive, electronics, and aerospace industries. The Japanese do not have a large defense industry, and they are concentrating on developing commercial materials for industrial applications. The domestic market for these MMC materials is small, but there are a few products in limited production.

Perhaps the most significant commercial development is the introduction by Toyota of diesel

Table 9-35.—Principal Organizations Involved in MMC Research in Japan, 1986

- Art Metal Manufacturing Co.
- B&W Refractories
- Daia Vacuum Engineering Co.
- Hiroshima University
- Honda Motors
- Japanese Society on Materials Science
- Mitsubishi
- Nippon Carbon
- Okura Laboratory
- Sumitomo
- Tokai Carbon
- Tokyo University
- Tokyo Institute of Technology
- Toyota Motors

SOURCE: Jerome Persh, Department of Defense, personal communication, November 1987.

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[31] Dural is scaling up to a capacity of 100,000 pounds per year of silicon carbide particulate-reinforced aluminum by the end of 1988.

[32] According to data supplied by Jacques Schoutens, Metal Matrix Composites Information Analysis Center, March 1987.

[33] According to data supplied by Jerome Persh, U.S. Department of Defense, November 1987.

engine pistons consisting of aluminum locally reinforced with ceramic fibers. The composite improves wear resistance, enabling elimination of nickel-cast iron inserts. The insert also reduces piston weight and increases thermal conductivity, improving engine performance and reducing vibration. Estimated annual production is about 300,000 pistons.[34] The example of the Toyota piston has stimulated a considerable worldwide interest in MMCs for pistons and other automotive parts. Components being evaluated include connecting rods, cam followers, cylinder liners, brake parts, and drive shafts.

Western Europe

Industry Structure

The structure of the Western European MMC industry is similar to that in the United States. Current MMC R&D is primarily funded by defense ministry contracts. Among end users, aerospace companies have made the highest R&D investments in MMCs. No automobile companies appear to have plans to use MMCs in the near future, although nearly all have undertaken limited evaluations. The principal countries involved in MMC research and development are the United Kingdom, France, and West Germany. Table 9-36 identifies the principal organizations involved in MMC research in Western Europe.

European Cooperative Programs

There is a joint European MMC research project within the BRITE program. It is a basic research program on silicon carbide-reinforced titanium. Participants include three government research laboratories—the Atomic Energy Research Establishment at Harwell (UK); Office Nationale d'Etudes et des Recherches Aerospatiales (ONERA, F), Deutsch Forschungs und Versuchsanstalt für Luft und Raumfahrt (DFVLR, FRG), and two companies—Sigma Fiber Supply (FRG) and IMI Titanium (UK).

Another joint effort is being conducted within the aerospace industry. It is solely for basic research and is funded at the equivalent of $800,000. The companies involved are British Aerospace, Westland Helicopters (UK), Rolls Royce (UK), Aerospatiale (F), and Motoren und Turbinen Union (MTU, FRG).

Table 9-36.—Principal Organizations Involved in MMC Research in Western Europe, 1986

Federal Republic of Germany
- Batelle-Frankfurt
- Berghof GMBH
- Dornier
- Messerschmitt-Bolkow-Blohm
- Sigri

France
- Aerospatiale
- CDF Chimie
- Ecole des Mines (Paris)
- Elf Aquitaine
- Institute St. Louis
- Societé Nationale des Poudres et Explosifs
- Thomson-CSF
- Université de Bordeaux
- Vetrotex-St. Gobain

Italy
- Aeritalia
- Fiat
- Siai Machetti

Netherlands
- Fokker

Norway
- Central Institute for Industrial Research-Oslo

Sweden
- Chalmers University of Technology
- Kockoms Shipyard
- SAAB
- Sweden Defense Laboratory
- Sweden Institute for Metals Research
- Volvo Flygmotor

Switzerland
- Ciba-Geigy

United Kingdom
- Harwell
- Bristol Composites
- British Aerospace
- Courtaulds
- Dunlop
- Fothergill & Harvey
- Hepworth & Grandage
- Imperial Chemicals
- Lagstall Engineering Co.
- Rolls Royce
- Royal Aircraft Establishment
- Wellworthy Ltd.
- Westland Helicopters

SOURCE: Jerome Persh, Department of Defense, personal communication, November 1987.

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[34] Carl Zweben, General Electric Co., "Metal Matrix Composites," a contractor report prepared for OTA, October 1986.

National Programs

United Kingdom.—In addition to those companies listed in table 9-35, several other companies have MMC efforts under way. Alcan U.K. is producing prototype silicon carbide particulate-reinforced aluminum using a spraying process and is planning to scale up to production by 1989. Two other large British metals companies are also planning to enter the MMC business. Cray (no relation to Cray computers) owns a division called Cray Advanced Materials which has a production facility for MMCs. Using an infiltration process, Cray is developing MMC torpedo hulls in conjunction with the Ministry of Defence. Cray uses many different types of continuous fiber: graphite, alumina, Nicalon, silicon carbide, and boron. A second company, BNF, is a research-only firm (similar to Battelle in the United States), which has some casting facilities for glass and silicon carbide fiber-reinforced composites.

France.—Pechiney, a large French aluminum company, has an MMC division that intends to produce particulate-reinforced composites. Aerospace companies with MMC programs include Dassault (manufacturer of the Mirage fighter), Turbo Mecha (an engine supplier), and Aerospatiale. Not all of these efforts are in-house; Dassault, for instance, is considering buying MMCs from the U.S. company DWA Composite Specialties.

West Germany.—In West Germany, the two main companies showing an interest in MMCs are Messerschmitt-Boelkow Blohm (an airframe manufacturer) and MTU (an engine supplier). Sigma Fiber Supply is a small company developing silicon carbide fiber for use in MMCs.

APPENDIX 9-1: RECENT JOINT RELATIONSHIPS IN THE U.S. ADVANCED CERAMICS INDUSTRY

Table A.—Acquisitions

Buyer	Company	Reason	Date
Air Products	Materials Technology	CVD coatings	1985
Air Products	San Fernando Labs	CVD technology	1986
Alcoa	Ceraver (now SCT) (F)	Manufacturing technology Extrusions	
Alcoa	PAKCO	Manufacturing technology	1986
AVX	Monolithic Components	Electronics	1984
Bayer, AG (FRG)	Montedison, S.P.A (I)	Manufacturing technology	N/A
Bayer, AG (FRG)	H.C. Starck (FRG) (90%)	Zirconia technology	1985
Borg-Warner	Fine Particle Tech. (25%)	Inject-mold ceramic auto parts	1985
Cabot	Augat Tech. Ceram.	Electronic packages	1985
Cabot	Spectrum Ceramics	Electronic packages	1985
Cabot	Rhode Island Elect. Ceramics	Electronic packages	1985
Coors	Alumina Ceramics	Manufacturing technology	N/A
Coors	RI Ceramics	Manufacturing technology	N/A
Coors	Royal Worcester Int. (UK)	Manufacturing technology	N/A
Coors	Siemens Components (FRG)	N/A	N/A
Coors	Wilbanks Int.	Manufacturing technology	N/A
Dow Chemical	Boride Products	Manufacturing technology	1985
Du Pont	Solid State Dielectr.	Ceramic capacitors	1982
Elkem Metals	Ceramatec (minority position)	Ceramic parts	1983
Ford	Ceradyne (minority position)	Heat engine	1986
General Electric	3M (part of ceramic business)	Electrical packages, structural	1983
W.R. Grace	Diamonite	Manufacturing technology	1983
Horsehead Industries	ARCO Chemical	Manufacturing technology	1986
ICI Australia Ltd.	Ferro Corp	Zirconia operations	1986
Iscar Metals (IS) (Iscar Ceramics)	Adv. Ceramic Systems	Manufacturing technology	1983
Koppers Co.	Ceramatec (minority position)	Heat engine	N/A
LRC	Crystalate	Aluminas	1984
Morgan Matroc Ltd. (UK)	Duramics	Ceramic parts	1986
Norton	Plasma Materials Inc.	Plasma process	1986
Pure Industry (Stackpole)	Frenchtown Amer.	High alumina technical ceramics	1985
Raychem	Interamics	Electronics	1984
Thomas & Skinner	Ceramic Magnetics	Magnetic ceramics	1985
Thomas & Skinner	Electron Energy	Electronic magnetic ceramics	1985

Table B.—Joint Ventures

Partner 1	Partner 2	Reason	Date
Alcan	Lanxide	Technology	1985
Alcoa	American Ceramic Tech.	Technology Production (electronics)	1986
Alcoa	Intercon X	IC ceramic packages	1986
Cercom, Inc.	Intercon X	Silicon nitrides and other refractories	1986
Coors	Started new companies in Scotland, Wales, Brazil		N/A
Corning	Plessco Optronics	Fiber optics	1986
Cummins Engine	Toshiba (J)	Technology	1986
General Motors Allison Gas Turbine Division	Int. Energy Agency (with West Germany and Sweden)	Powder characterization	Ongoing
W.R. Grace	Dynamit Nobel (FRG)	High-purity silicon	1983
W.R. Grace	Feldmuehle (FRG)	Heat engine	1983
Hitachi (J)	SOHIO Eng. Mat. (Carborundum)	SiC ceramics	1983
Koppers Co.	Adv. Refrac. Mat.	Powders	N/A
Montedison (I)	Keramont	Powders, products	1986
Norton	TRW	Heat engine	1985
Olin Corp.	Asahi Glass (J)	Electronics	1986

Table C.—Licensing Agreements

Licensor	Licencee	Reason	Date
ARCO Chemical	Martin Marietta	Advanced ceramic composites for tooling and other wear applications	1986
ARCO Chemical	Sandvik, AB (S)	SiC whisker reinforcements	1986
ASEA Cerama (S)	Norton	Glass encapsulation HiP process	N/A
Centre Suisse D'Elect. et Microelect.	Air Products	Chemical vapor deposition (CVD) technology	1986
Greenleaf Corp.	ARCO Chemical	Manufacture and sale of SiC whisker-reinforced ceramic tooling	1986
Iscar Ceramics (IS)	Ford	Cutting tool technology	1986
Lucas (UK)	Kennametal	Sialon technology	N/A
Lucas (UK)	Norton	Hot pressed silicon nitride	1970
People's Republic of China	Corning	Complete factory	1986
PPG	Alcoa	Plasma powder production	1986
ROC TEC (Kelsey-Hayes subsidiary)	Dow Chemical	Powder processing technology	1985
SEP (F)	Du Pont	Ceramic composites	1987

N/A = Not available.

KEY: A = Austria; B = Belgium; F = France; FIN = Finland; FRG = West Germany; I = Italy; IR = Ireland; IS = Israel; J = Japan; NL = Netherlands; S = Sweden; SP = Spain; SWI = Switzerland; T = Taiwan; UK = United Kingdom; US = United States.

SOURCE: Business Communications Co., Inc., "Strategies of Advanced Materials Suppliers and Users," a contractor report prepared for OTA, Mar. 24, 1987.

APPENDIX 9-2: RECENT JOINT RELATIONSHIPS IN THE JAPANESE ADVANCED CERAMICS INDUSTRY

Table A.—Joint Ventures

Joint venture partners	Company formed	Business	Date
Harima Refractories/ Nippon Steel	Micron	Manufacturing and distributing ceramic powders	1985
Hitachi Chemical/ Carborundum (SOHIO)	Hitachi Carborundum[a]	Manufacturing and distributing silicon carbides	N/A
Nippon Steel/ Kurosaki Refractories/ Nippon Steel Chemical	N/A	Development of production method for new ceramics by sol-gel process	N/A
Sumitomo Chemical/ SFE Technology	Sumika SFE	Manufacturing and distributing multilayered ceramic capacitors	1985
Toshiba Ceramics/ Kyoritsu Ceramics	STK Ceramics Laboratories	R&D of fine ceramic materials	1985
Toshiba Ceramics/ SOHIO Engineered Materials	N/A	Ceramic fibers	N/A
Yuasa Battery/ NGK Spark Plug	Ceramic Battery	Sodium-sulfur batteries	N/A

[a] Carborundum (SOHIO) sold its share of the joint venture to Hitachi Chemical in April 1986.

N/A = Not available.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table B.—Licensing Agreements

Licensor	Licensee	Agreement description	Date
British Nuclear Fuels Ltd. (UK)	Asahi Glass	Technology for reaction sintering	1985
Gateng Instrument (FRG)	Nippon Sheet Glass	Calcining technology for zirconium oxide	1985
Lucas-Cookson-Syalon (UK)	Sumitomo Electric	Sialon powders and products	1985
	Nippon Steel	Sialon powders and products	1985
	Hitachi/Hitachi Metals	Sialon powders and products	1985

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

APPENDIX 9-3: RECENT JOINT RELATIONSHIPS IN THE WESTERN EUROPEAN ADVANCED CERAMICS INDUSTRY

Table A.—Acquisitions

Buyer (loc.)	Company	Primary business	Date
Alcoa (SWI)	Ceraver (F)	Ultrafiltration ceramic membranes	1986
Bayer (FRG)	Cremer Forschungsinstitut (FRG) (75% share)	Research laboratory and family holdings	1986
Bayer (FRG)	Annawerke (FRG) (through Cremer purchase)	Technical ceramics	1986
Bayer (FRG)	Friedrichsfeld (FRG) (through Cremer purchase)	Technical ceramics	1986
Bayer (FRG)	Starck (FRG) (90% share)	Special metallurgical powders	1986
Coors (UK)	Royal Worcester (UK)	Industrial ceramics	1983
Fairey (UK)	Allied Insulators (UK)	Insulators	1985
Feldmuehle (FRG)	Part of Annawerke (FRG)	Silicon nitride technology	1984
Hoechst (FRG)	Rosenthal Technik (FRG) (90% share)[a]	Advanced ceramics, including electronic substrates and automotive components	1983
ICI (Australia)[b]	Ferro's Bow, NH plant[c]	Zirconia powders	1986
Lucas (UK)	Cookson-Syalon (UK)[d]	Licensing of sialon patent, prototypes, and limited part production	1982
Pechiney (F)	Desmarquest (F)	Technical ceramics	1985
Rauschert (FRG)	Part of Annawerke (FRG)	Textile guides	1984
Rhone-Poulenc (F)	Ceraver's non-oxide technologies[e]	Technology for nitrides of silicon, aluminum and others, and lab equipment	1985
Schunke (FRG)	Dyko Ingenieur Keramik (FRG)	Technical ceramics	1983
Stettner (FRG)	CICE (F)	Electrical ceramics	1985
St. Gobain (F)	Kerland (F)	Ceramic fibers	1985
St. Gobain (F)	SEPR (F)	Refractories, zirconia beads	1985
Ziegelwerke Horw-Gettnau-Muri (SWI)	Metoxid (SWI)	Engineering ceramics; mainly tin oxides	1986[f]
VAW (FRG)	Didier (FRG) (15% share)	Refractories	1985

[a] New comany name is Hoechst CeramTec.
[b] Owned 64% by ICI, UK.
[c] New company name is Z-Tech.
[d] New company name is Lucas-Cookson-Syalon.
[e] New company name is Ceramiques et Composites.
[f] Acquired in two steps in June and September.

Table B.—Joint Ventures

Joint venture partners	Company formed	Business	Date
ASEA (50%)/Boliden, Nobel, Sandvik, SKF, and Volvo (each 10%) (all S)	ASEA Cerama (S)	High performance ceramics (HPC), particularly HIP techniques	1982
Belgian Government-Walloon Region (80%)/ Belref, Diamond, Boart, Gechem, Glaverbel (each 5%) (all B)	Neoceram (B)	Develop HPC business	1986
Brush-Wellman (US)/Heraeus (FRG)[a]	—	Develop aluminum nitride electronic substrate business in United States	1985
CICE (F)/Cabot (US)	CERDI (F)	Electronic substrates and packages Presently mainly selling packages from Cabot's subsidiary, Augat (US)	1986
Degussa (FRG)/Hutschenreuter (FRG)	—	Flue gas catalyst supports	1986
Dyko (FRG)/Morgan (UK)[b]	Dyko Morgan Faser Technik (FRG)	Vacuum-formed ceramic fibers	1983
Eurofarad (F) (5%)/Pechiney (F) (95%) (recently joined by Thomson-CSF)	Xeram (F)	Dielectric ceramics	1986
Frauenthal (A)/Simmering (A)	—	Catalytic converters for processing flue gases in power stations	1985
W.R. Grace (US) (50%)/Feldmuehle (FRG) (50%)	Grace/Feldmuehle/ Noxeram	Automotive engine parts	1983
ICI (Australia) (85%)[c]/Sirotech, (Australia) (15%)	Z-Tech (Australia)	Zirconia products	1985
Koor (IS)/Park Electrochemical (US)	—	Electronic ceramics	1984
Montedison (I)/EFIM (I)	—	Research and development for HPC for defense applications	1986
Philips (NL)/Nippon Chemi-Con (J)/ Nippon Steel (J)	PNN	Multilayer ceramic capacitors	1986
Rhone-Poulenc (F)/SEP (F)	—	Composite of SiC whiskers and ceramics	1986
SACMI (I)/POPPI (I)	—	Development of ceramics	1986
Thomson-CSF (F)/Lamination Specialties (US)	—	Soft ferrites	1985
Wade (UK)/Engelhard (UK)/British Steel (UK)	—	Steel-based ceramic substrates	1986
Waertsilae (Fin) (60%)/Partek (Fin) (40%)	WP Ceramics	Wear parts of alumina and zirconia	1986

[a] Started in June 1985 but terminated in December 1985.
[b] Morgan recently changed its name to Matroc.
[c] 64% owned by ICI (UK).

Table C.—Licensing Agreements

Licensor	Licensee	Product technology	Date
ASEA Cerama (S)	Norton (US)	Hot isostatic pressing (HIP) with glass encapsulation technology	1984
ASEA Cerama (S)	Seco Tools (S)	HIP with glass encapsulation technology	1985
ASEA Cerama (S)	GET (US)	HIP with glass encapsulation technology	1985
British Nuclear Fuels (UK)	Iscar (IS)	Silicon nitride for tool inserts	1983
Lucas-Cookson-Syalon (UK)	about 15 licensees throughout the world	Sialon technology	1982
Mitsubishi Petrochemical (J)/Hitachi (J)	Frauenthal (A)	Denox catalysts for power plant flue gas	1985
Mitsubishi Petrochemical (J)/Sakai (J)	Noxeram (FRG)	Smokestack emission catalysts	1986

KEY: A = Austria; B = Belgium; F = France; FIN = Finland; FRG = West Germany; I = Italy; IR = Ireland; IS = Israel; J = Japan; NL = Netherlands; S = Sweden; SP = Spain; SWi = Switzerland; T = Taiwan; UK = United Kingdom; US = United States.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

APPENDIX 9-4: RECENT JOINT RELATIONSHIPS IN THE U.S. ADVANCED COMPOSITES INDUSTRY

Table A.—Acquisitions

Buyer	Acquired company	Primary business	Date
Amoco	Carbon Fiber Group (Union Carbide)	Fibers	1986
BASF (FRG)	Celion Carbon Fibers Division, Narmco, Quantum (Celanese)	Fibers, prepregs, shapes	1985
British Petroleum (UK)	HITCO (Owens-Corning)	Fibers, prepregs, shapes	1986
Du Pont	Carbon Fiber Group (Exxon)	Fibers, shapes	1985
Hexcel	Dittmer & Dacy	Shapes	1984
Hexcel	Hi-Tech Composites	Ply fabrics	1986
ICI Americas	Fiberite Composite Materials (Beatrice)	Prepregs, fabrics	1985
Owens-Corning	HITCO (Armco)	Fibers, prepregs, shapes	1985
Shell[a]	Morrison Molded Fiber Glass	Pultruded shapes	1986
Textron	Avco	Shapes, prepregs, fibers	1985

[a] 80% interest.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table B.—Joint Ventures

Joint venture partners	Company formed	Primary business	Date
Celanese/Daicel Chemical Industries (J)	Polyplastics (J)	Polyphenylene sulfide (PPS) molding compounds	N/A
Celanese/Kuraray (J)	—	Development of aramid fibers	N/A
Dexter/Courtaulds (UK)	Hysol Grafil (US, UK)	Carbon fibers, prepregs	1983
Fiberite/Mitsubishi (J)	Kasei-Fiberite (J)	Prepregs	1983
Hercules/Biomet	—	Composite orthopedic implants	1986
Hercules/Sumitomo (J)	Sumika-Hercules (J)	Polyacrylonitrile (PAN) precursor, prepregs	N/A
Shell/Proform Composites	Xerkon	Composite shapes, woven fabrics	1984

N/A = Not available.

Table C.—Licensing Agreements

Licensor	Licensee	Agreement description	Date
HITCO	Formosa Plastics (T)	Carbon fiber, prepreg tape	1984
HITCO	Mitsubishi Rayon (J)	Carbon fiber technology	1981
Nikkiso (J)	Boeing	Carbon fiber technology	1986
Sumitomo (J)	Avco	Distribution of alumina fiber	N/A
Toho Rayon (J)	Celanese/BASF	Carbon fiber technology	N/A
Tokai Carbon (J)	Avco	Distribution of SiC whiskers	1986
Toray (J)	Union Carbide/Amoco	Carbon fiber technology	1979
Ube (J)	Avco	Distribution of ceramic fiber	1986

N/A = Not available.

KEY: A = Austria; B = Belgium; F = France; FIN = Finland; FRG = West Germany; I = Italy; IR = Ireland; IS = Israel; J = Japan; NL = Netherlands; S = Sweden; SP = Spain; SWI = Switzerland; T = Taiwan; UK = United Kingdom; US = United States.

APPENDIX 9-5: RECENT JOINT RELATIONSHIPS IN THE JAPANESE ADVANCED COMPOSITES INDUSTRY

Table A.—Joint Ventures

Joint venture partners	Company formed	Primary business
Asahi Chemical/Ciba-Geigy (SWI)	Asahi-Ciba	Epoxy
Asahi Chemical/Ciba-Geigy (SWI)	Asahi Composite	Prepregs
Mitsubishi Chemical/Fiberite (US)	Kasei-Fiberite	Prepregs, shapes
Mitsubishi Rayon/HITCO (US)	Dia-HITCO Composites	Shapes
Mitsui Petrochemical/Rhone-Poulenc (F)	Nippon Polyimide	Polyimides
Sumitomo Chemical/Hercules (US)	Sumika-Hercules	Carbon fibers, precursors, prepregs
Toho Rayon/Narmco (US)	Toho Badische	Prepregs, shapes
Toray/Du Pont (US)	Toray Du Pont	Aramid fibers
Toray/Phillips (US)	Toray Phillips	Polyphenylene sulfide

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table B.—Licensing Agreements

Licensor	Licensee	Agreement description	Date
Hercules (US)	Sumika-Hercules	Production technology for carbon fibers	1979
HITCO (US)	Mitsubishi Rayon	Calcining technique for carbon fibers	1981
Nikkiso	Boeing (US)	Production technology for carbon fibers	1986
Sumika-Hercules	Hercules	Supplying precursor	1979
Toho Rayon	Celanese/BASF (US)	Production technology for carbon fibers	N/A
Toho Rayon	Enka (NL)	Production technology for carbon fibers	1980
Toray	Société des Fibres de Carbones (F)	Production technology for carbon fibers	1983
Toray	Union Carbide/Amoco (US)	Production technology for carbon fibers	1979

N/A = Not available.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

APPENDIX 9-6: RECENT JOINT RELATIONSHIPS IN THE WESTERN EUROPEAN ADVANCED COMPOSITES INDUSTRY

Table A.—Acquisitions

Buyer	Acquired company	Business	Date
BASF (FRG)	Celanese's advanced materials business (US)	Fibers, prepregs, shapes	1985
BP Group (UK)	Bristol Advanced Composites (UK)	Prepregs	1985
British Petroleum (UK)	HITCO (US)	Fibers, prepregs, shapes	1986
Ciba-Geigy (SWI)	Aero Research (UK)	Composite weaver	1947
	Brochier (F)		1982
Courtaulds (UK)	Fothergill & Harvey (UK)	Composite parts weaver	1987
Dow Chemical Europe	Seger & Hoffman (SWI)	Prepregs	1984
Hexcel (US)	Stevens-Genin (F)	Prepregs	1985
ICI Americas (subsidiary of ICI, UK)	Fiberite (Beatrice) (US)	Prepregs	1985
Montedison (I)	Texindustria (I)	Weaver	1985
Sturgis und Teschler (FRG)	Interglas-Textil (FRG)	Weaver	1981

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Table B.—Joint Ventures

Joint venture partners	Agreement description	Date
Akzo (Enka) (NL)/Toho Rayon (J)	Joint venture for carbon fiber products	1982
Courtaulds (UK)/Dexter Hysol (US)	Carbon fiber venture Hysol-Grafil	1983
DSM (NL)/Toyobo (J)	High-strength polyethylene fiber	1985
Elf Aquitaine (F)/Toray (J)	Joint venture for carbon fiber production	1982

Table C.—Licensing Agreements

Licensor	Licensee	Agreement description	Date
Aerospatiale (F)	Hercules (US)	Three-dimensional weaving technology	1984
Bell Helicopter (US)	Agusta (I)	Helicopter construction technology	N/A
Hercules (US)	CASA (SP)	Carbon fiber technology	1987
Narmco Materials (US)	Fibre & Mica (F)	Prepregging technology	N/A
Toho Rayon (J)	Enka/Akzo (NL)	Carbon fiber technology	1982

N/A = Not available.

KEY: A = Austria; B = Belgium; F = France; FIN = Finland; FRG = West Germany; I = Italy; IR = Ireland; IS = Israel; J = Japan; NL = Netherlands; S = Sweden; SP = Spain; SWI = Switzerland; T = Taiwan; UK = United Kingdom; US = United States.

SOURCE: Strategic Analysis, Inc., "Strategies of Suppliers and Users of Advanced Materials," a contractor report prepared for OTA, Mar. 24, 1987.

Chapter 10

Collaborative Research and Development: A Solution?

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Chapter 10

Collaborative Research and Development: A Solution?

FINDINGS

Since the early 1980s, numerous collaborative R&D programs involving combinations of government, university, and industry participants have been initiated. These programs have a variety of institutional structures, including university-based consortia, quasi-independent R&D institutes (often funded by State government sources), and Federal laboratories. Such collaborative efforts offer a number of potential contributions to U.S. industrial competitiveness, including an excellent environment for training students, an opportunity for each stakeholder to leverage his R&D investment, and research results that could lead to new commercial products. Collaborations are often seen as a bridge that can facilitate the translation of basic research into commercial products.

The extent to which commercialization is a goal of collaborative R&D programs depends both on each program's organizational structure and the economic incentives perceived by the participating companies. Most current collaborative programs in advanced materials technologies are university-based consortia or are located within Federal laboratories. According to a sampling of collaborative advanced materials, microelectronics, and biotechnology programs undertaken by OTA, neither the programs' staffs nor their industrial participants rank commercialization of research results high on their lists of priorities; furthermore, neither party systematically tracks commercial outcomes. By and large, the industrial participants value their access to skilled research personnel and graduate students more highly than the actual research results generated by the collaboration. This strongly suggests that such collaborative programs should not be viewed as engines of commercialization and jobs, but rather as a form of ''infrastructure support,'' providing industry with access to new ideas and trained personnel.

According to the OTA sampling, the programs' industrial participants often have only a modest amount of involvement in the planning and operation of the collaborative programs. For the most part, they approach their relationship with the research performing organizations as being a ''window to the future.'' Furthermore, ''collaboration'' may be an inaccurate description of the programs studied. In large measure, the programs do not involve intense, bench-level interaction between institutional and industrial scientists; rather, the nature of the collaboration seemed to be mostly symbolic.

In many cases, a desire for commercial outcomes does not seem to drive how collaborative programs are managed or how issues of intellectual property, project selection, etc. are addressed. Many of the university-based programs concentrate on publishable research and graduate training, while those programs based in Federal facilities are only now beginning to move away from their primary agency missions toward a broader concern with U.S. industrial competitiveness.

There are exceptions to these general observations in some of the newer programs in university-based consortia and quasi-independent R&D organizations that conduct both generic and proprietary research in parallel within the same program. Often undertaken in conjunction with State government funding, these organizations incorporate a greater commitment to commercialization and economic development in their mission. This suggests that if commercialization is in fact one of the goals of collaboration, it needs to be a much more organic part of research-performing organizations rather than merely an added-on element.

For the products of collaborative research to be commercialized, there must be a corresponding capacity and willingness on the part of the industrial participants. However, only about 50 percent of the advanced materials company participants interviewed by OTA reported any follow-on work stimulated by collaboration.

Overwhelmingly, OTA's industrial respondents did not feel that changes in institutional arrangements with research performing programs would be an important lever in facilitating the commercialization process. Rather, they perceived that the critical issue revolves around an economic problem: how companies, particularly in the advanced materials area, can justify the cost of major investments in R&D and new manufacturing facilities in light of uncertain markets. This highlights the fact that effective commercialization of collaborative R&D requires not only a smooth path for technology transfer from the R&D center to its industrial participants, but also strong economic incentives within the companies to develop the technology.

INTRODUCTION[1]

Conventional wisdom states that one reason for flagging industrial competitiveness in the United States is industry's failure to make full use of a first-class domestic science base. Critics note that many technologies developed in the United States are commercialized abroad, and that the open laboratories of the best U.S. research universities and Federal laboratories are visited far more frequently by foreign industry scientists than by U.S. industry scientists. These critics also argue that other countries have a much closer coupling between their research laboratories and industrial production lines. Thus, if the United States does not greatly improve its level of technology utilization, it may continue to produce more new ideas, but may also remain behind its competitors in the commercial exploitation of those ideas.

Collaborative R&D programs involving government, universities, and industry have been touted as the most effective means of bridging this gap.[2] Since the early 1980s, numerous collaborative R&D programs have been initiated in a variety of technologies, including microelectronics, biotechnology, and advanced materials.[3]

This chapter presents the results of an OTA survey of a sample of such programs, to assess the roles and expectations of government, university, and industry stakeholders. The principal question addressed was: What impacts do collaborative research programs have on the translation of basic research into commercial products in these high technology areas?

Collaborations often bring together partners that have very different attitudes and goals.[4] Traditionally, research universities—and to some extent Federal laboratories, as well—have been concerned with the advancement of science and technology for its own sake; in contrast, R&D departments in industry have been oriented toward product development for the market.[5] One assumption of collaborative R&D programs is that these perspectives will somehow merge, creating a seamless continuum from which innovations can flow.

There are several factors that make collaborative programs an attractive way for industries to supplement their R&D efforts:

1. The high cost of doing research today makes it increasingly difficult for a single company to "go it alone."

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[1] The discussion in this chapter draws heavily from Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," a contractor report prepared for OTA, February 1987.

[2] See, for example, Lansing Felker, "Cooperative Industrial R&D: Funding the Innovation Gap," *Bell Atlantic Quarterly*, vol. 1, No. 2, winter 1984.

[3] For a recent review, see the Government-University-Industry Round Table, *New Alliances and Partnerships in American Science and Engineering* (Washington, DC: National Academy Press, 1986).

[4] A review of the barriers to industry/university research relationships may be found in Donald R. Fowler, "University-Industry Research Relationships," *Research Management*, February 1984.

[5] However, there are wide variations within these generalizations; for instance, there are universities with a strong applied research orientation, and companies that conduct a significant amount of basic research.

2. The collaboration allows each partner or stakeholder to leverage his investment manyfold.
3. Many research problems require a multidisciplinary approach; a collaborative program can bring together a "critical mass" of researchers with complementary talents and expertise.
4. Collaborations give a company access to new ideas and also to graduate students whom it may wish to hire.
5. The time horizon of collaborative R&D efforts can be intermediate- to long-term, in contrast to the short time horizons typically imposed on individuals engaged in industrial research.

Although commercialization of research and job creation are often touted as major benefits of collaboration, it would not be appropriate to evaluate all collaborative programs by these two criteria. Federal laboratories, which represent a significant subset of the programs in the forefront of advanced materials research, historically have been discouraged from involving themselves with commercial development, although industry has sometimes been able to use Federal facilities on a full cost reimbursement basis. In recent years, there has been a growing recognition of the contribution that Federal laboratories could make to U.S. industry's ability to compete in international markets.[6] [7] [8] With the passage of the Stevenson-Wydler Act of 1980 (Public Law 96-480) and the Technology Transfer Act of 1986 (Public Law 99-502), the culture of the Federal laboratories appears to be shifting toward incorporating U.S. industrial competitiveness as a goal along with their traditional missions.

Although collaborative R&D arrangements involving government, academia, and industry have received a great deal of attention recently, they are not a new phenomenon. The original model for much collaborative government/university/industry R&D work is the National Agricultural Extension Service program, which can be traced back in various forms to the 1880s. It was not until World War II, though, that major Federal research efforts were initiated. These included collaborations between government and academia, as well as the creation of the large Federal laboratory system, including Oak Ridge, Sandia, Los Alamos, and Lawrence Livermore, tied to the Defense establishment.

In the postwar years, the steady growth of Federal research spending through the National Science Foundation (NSF) and the Department of Defense encouraged the proliferation of university research facilities. During the same period, industrial laboratories grew substantially, but beyond specific contracts and consulting arrangements, they had few institutional connections.

Major trade and industry associations emerged during this postwar period to concentrate talent and resources in particular areas, but active collaboration among industrial firms continued to be inhibited by antitrust considerations. The emergence of the industry associations as neutral research brokers was a response to these concerns.

In the mid-1970s, NSF's Research Applied to National Needs (RANN) program began to experiment with various cooperative ventures. The RANN program represented an attempt by NSF to expand its traditional base in academic basic research to a range of other research approaches. However, this initiative coincided with a period of budget stringency, and RANN programs began to be perceived as competitors to traditional basic research programs—the primary thrust of NSF's mission—rather than as new opportunities. Thus, only a few RANN programs were sustained, among them the University/Industry collaborative programs, largely because they were able to point to successful leveraging of industry funds for research in universities.[9]

NSF's current Engineering Research Center (ERC) initiative adopts something from the earlier University/Industry collaborative model, particularly the idea of industrial liaison.[10] However, in its provision of indefinite Federal funding (as opposed to phasing out Federal support after 5 years), and the lack of industrial leverage over research agendas, the ERC program resembles traditional university-oriented NSF programs more than do the University/Industry Cooperative Research programs.

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[6] Joseph Morone and Richard Ivins, "Problems and Opportunities in Technology Transfer from the National Laboratories to Industry," *Research Management*, May 1982.

[7] Herb Brody, "National Labs, At Your Service," *High Technology*, July 1985.

[8] Paul A. Blanchard and Frank B. McDonald, "Reviving the Spirit of Enterprise: Role of the Federal Labs," *Physics Today*, January 1986.

[9] For a recent review, see Robert M. Colton, "University/Industry Cooperative Research Centers Are Proving Themselves," *Research Management*, March-April 1987.

[10] Lewis G. Mayfield and Elias Schutzman, "Status Report on the NSF Engineering Research Centers Program," *Research Management*, January-February 1987.

Relative newcomers to the collaborative R&D effort are a variety of State programs, such as Ohio's Edison Centers and Pennsylvania's Ben Franklin Partnerships. Along with more focused initiatives such as the Microelectronics Center of North Carolina, these new State programs represent some of the more innovative developments.[11] They support a mixture of basic and applied research, and are focused particularly on job creation and economic development, usually in the high technology sector.

Although gross Federal R&D has been increasing, the share of Federal support going to universities has declined one percentage point per year for the past several years.[12] This has stimulated university interest in securing industrial funding through collaborative programs. At the same time, legislative changes have reduced antitrust concerns inherent in industrial collaboration in R&D and have improved the patent incentives for commercialization of the research.[13] These changes have produced a climate favoring various collaborative models, and the visibility of several of these efforts, such as the Microelectronics and Computer Corp. (MCC) and NSF's ERC program, have become quite high.

Many different models for collaborative R&D are currently being explored.[14] These include "one-on-one" joint projects involving a company and a university, small business incubator programs associated with research universities, quasi-independent research institutes associated with universities, private sector consortia, and multidisciplinary centers based at universities and national laboratories. These models differ widely in their goals, procedures, and sources of funding.

Table 10-1 outlines some salient characteristics of four common models of collaborative R&D:

Table 10-1.—Characteristics of Four Prominent Models of Collaborative R&D

	Trade/industry associations	University-based consortia	Quasi-independent institutes	Federal laboratories
Start	1960s	1970s	1980s	1940s
Scale of program	$5 million plus	$1-$5 million	$3-$10 million	$10-$100 million
Site of research	usually universities	universities	universities or special facilities	own facilities or contracts
Focus of research	applied to development	basic to applied	applied	basic to development
Performers	usually academics	academics/students	academics/full-time staff/students	full-time staff/contractors
Patent rights	association	university/members	research performers	government/industry
Major accountability	industry through board	university, indirect to industry sponsors	sponsors (often State government)	Federal Government/agency missions
Commercialization interest	high	generally low	generally high	low except where needed for mission
Major products	products/processes	research reports/students	research reports	products/processes
Planning horizon	2-3 years	1-2 years	1-4 years	2-10 years
Proprietary work	yes, mostly	not usually	sometimes	not usually, but often classified
Funding sources	industry members	mostly Federal Government, some industry	State government, industry	Federal appropriation
Dissemination mechanisms	industry visits, personnel exchanges	seminars, publications	visits, some exchanges, publications	limited exchanges, seminars, some publications

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

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[11] Walter H. Plosila, "State Technical Development Programs," *Forum for Applied Research and Public Policy*, summer 1987.

[12] Erich Bloch, "New Strategies for Competitiveness: Partnerships for Research and Education," an address to the New York Science Policy Association, New York Academy of Sciences, Jan. 20, 1987.

[13] The National Cooperative Research Act of 1984 (Public Law 98-462) permitted companies to form joint ventures for R&D. In 1980, Public Law 96-517 amended the U.S. Code to permit small businesses and non-profit organizations to hold title to patents resulting from Federal grants and contracts; in 1983, this policy was extended to all Federal R&D contractors.

[14] For an overview, see Herbert I. Fusfeld and Carmela S. Haklisch, "Cooperative R&D for Competitors," *Harvard Business Review*, November-December 1985.

trade/industry associations, university-based consortia, quasi-independent institutes, and Federal laboratories. Some models are more prominent in particular technologies. For example, collaborative advanced materials R&D is often carried out in multidisciplinary centers based at universities and Federal laboratories, while collaborative microelectronics and biotechnology R&D are more often associated with private sector consortia, quasi-independent institutes, and one-on-one university/company relationships. The suitability of a given model depends on several technology-specific variables, such as the maturity of the technology, the costs of R&D and production scale-up, and private sector expectations regarding the size and timing of potential markets.

Since the early 1980s, there has been an explosion of collaborative R&D efforts in advanced materials fields. For instance, table 10-2 lists some advanced materials programs that have been ini-

Table 10-2.—Examples of Recent Advanced Materials Programs[a]

State	Program	Location	Year founded	Program emphasis
California	Center for Advanced Materials, Lawrence Berkeley Laboratory	U. of California, Berkeley	1983	Electronic materials, structural materials, and catalysts
Colorado	Advanced Materials Institute	Colorado School of Mines	1984	Interdisciplinary materials research
	University-Industry Cooperative Steel Research Center	Colorado School of Mines	1985	Thermomechanical processing and alloying effects on properties and deformation behavior
Delaware	ERC for Composites Manufacturing Science and Engineering	U. of Delaware/Rutgers U.	1985	Processing, fabrication, and testing of polymeric and composite materials
Florida	Bio-Glass Research Center	U. of Florida, Gainesville	1983	Biocompatible ceramic materials
Illinois	Basic Industry Research Institute	Northwestern U.	1984	Technology for basic auto, metal, and construction industries
	ERC for Compound Semiconductor Microelectronics	U. of Illinois	1986	Advanced electronic materials
Massachusetts	Polymer Processing Program	Massachusetts Institute of Technology	1976	Synthesis of new processes, interdisciplinary research
	Materials Processing Center	Massachusetts Institute of Technology	1980	Generic materials processing in metals, ceramics, polymers, electronic materials, and composites
	Polymers Program	U. of Massachusetts	1980	Synthesis of new functional polymers, polymer composites
New Jersey	Center for Ceramics Research	Rutgers U.	1984	Automotive engine parts, computer components, optical fibers
New York	Center for Composite Materials	Rensselaer Polytechnic Institute	1986	High-temperature structural composites
	Center for Advanced Technology in Ceramic Materials	Alfred U.	1987	Advanced ceramics research
Ohio	Polymer Innovation Corp.	U. of Akron/Case-Western Reserve U.	1984	Macromolecules, polymer blends, composites
	Welding Center	Ohio State U.	1984	Welding, joining of advanced materials
	ERC for Near-Net Shape Manufacturing	Ohio State U.	1986	Manufacturing sciences
Pennsylvania	Center for Advanced Materials	Penn State U.	1986	High-temperature engineering materials
	Materials Research Laboratory	Penn State U.	1964	Dielectrics, structural ceramics, advanced materials
	Consortium on Chemically Bonded Ceramics	Penn State U.	1986	High-strength cementitious materials

[a] Supported by Federal, State, and industry sources.

ERC: Engineering Research Center (sponsored by the National Science Foundation).

SOURCE: Adapted from R.M. Latanision, "Developments in Advanced Materials in the Industrialized Countries," a paper presented at the Federation of Materials Societies' 9th Biennial Conference on National Materials Policy, Fredericksburg, VA, Aug. 4-7, 1986.

tiated in recent years. Most of these are associated with universities and involve combinations of Federal, State, and industrial support. There has been little attempt to coordinate these efforts, and consequently there has been some overlapping in research agendas as well as in sources of industrial funding. This has given rise to concern that such a fragmented approach is wasteful, will dilute resources, and will fail to generate the results necessary to make a competitive difference for the United States in the international marketplace.[15] This issue is discussed further in chapter 12.

The Federal laboratories within the Departments of Energy, Commerce, Defense, and the National Aeronautics and Space Administration also conduct extensive advanced materials research programs in support of their various missions. They are important resources of facilities and expertise, especially in advanced ceramics and composites technologies. Federal laboratories are especially important in advanced ceramics research: in 1985, for instance, Federal laboratories accounted for 30 percent of the total Federal budget of $51 million for structural ceramics R&D.[16] Of the Federal laboratories conducting research, only the National Bureau of Standards within the Department of Commerce has a mission explicitly directed toward industry.

Three industrial consortia focusing on advanced ceramics R&D are being planned at this writing. These are the Ceramic Advanced Manufacturing Development and Engineering Center (CAMDEC), which intends to focus on processing and manufacturing technology and will be located at Oak Ridge National Laboratory; the Advanced Ceramic and Composite Partnership (ACCP), part of the Midwest Technology Development Institute, a consortium funded by nine Midwestern States and based in St. Paul, MN; and the National Applied Ceramic Research Association (NACRA), based in southern California. Discussions are currently underway among the three consortium organizers, officers of the United States Advanced Ceramics Association, and the U.S. Department of Commerce as to how the agendas of these consortia can be coordinated. Because these efforts are in an early stage, the consortia membership rosters are still incomplete. Many of the prospective member companies are already participating in various other collaborative programs, and they are uncertain about which arrangements would offer them the best return on investment.

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[15] R.M. Latanision, "Developments in Advanced Materials in the Industrialized Countries," a paper presented at the Federation of Materials Societies' Ninth Biennial Conference on National Materials Policy, Fredericksburg, VA, Aug. 4-7, 1986.

[16] According to unpublished data compiled by S.J. Dapkunas, National Bureau of Standards.

COLLABORATIVE RESEARCH AND DEVELOPMENT: SURVEY RESULTS

To provide a current basis for examining collaborative R&D efforts as a factor in enhancing the competitiveness of U.S. advanced materials industries, OTA undertook independent surveys of individuals representing the three principal stakeholders in the process: research-performing organizations, industry participants, and government policymakers with long experience in collaborative research programs. In all, OTA examined a total of 19 research-performing organizations engaged in collaborative R&D, consisting of 11 in advanced materials, and, for purposes of comparison, 4 each in information technology and biotechnology. These are identified in table 10-3, and they represent three of the model types discussed earlier: the university-based consortia, quasi-independent institutes, and Federal laboratories. In addition, OTA interviewed—in separate surveys—representatives of 19 industrial collaborators of these research-performing organizations, plus 9 government policymakers, as shown in table 10-4.

Given the range of collaborative models and technologies, as well as the small sample of research-performing organizations and industry

Table 10-3.—Collaborative Research-Performing Organizations Surveyed by OTA

Organization	Model type	Location
Advanced materials:		
Center for Ceramics Research, Rutgers University	University-based consortium	Piscataway, NJ
Center for Composites Manufacturing Sciences and Engineering, University of Delaware	University-based consortium	Newark, DE
Center for Composite Materials and Structures, Virginia Polytechnic Institute	University-based consortium	Blacksburg, VA
Center for Applied Polymer Research, Case-Western Reserve University	University-based consortium	Cleveland, OH
Center for Dielectrics, Pennsylvania State University	University-based consortium	University Park, PA
Materials Science Department, Massachusetts Institute of Technology	University-based consortium	Cambridge, MA
Materials Laboratory, Wright-Patterson Air Force Base	Federal laboratory	Wright-Patterson AFB, OH
High Temperature Materials Laboratory, Oak Ridge National Laboratory	Federal laboratory	Oak Ridge, TN
Center for Materials Science, National Bureau of Standards	Federal laboratory	Gaithersburg, MD
Materials Processing Division, Sandia National Laboratory	Federal laboratory	Albuquerque, NM
Materials Research Program, NASA-Lewis	Federal laboratory	Cleveland, OH
Biotechnology:		
Biomedical Technologies Consortium, University of Utah	University-based consortium	Salt Lake City, UT
Center for Biotechnology Research/Engenics	Quasi-independent institute	Menlo Park, CA
Center for Advanced Research in Biotechnology	Quasi-independent institute	Rockville, MD
Michigan Biotechnology Institute	Quasi-independent institute	Lansing, MI
Information technology:		
Center for Integrated Systems, Stanford University	University-based consortium	Palo Alto, CA
Magnetics Technology Laboratory, Massachusetts Institute of Technology	University-based consortium	Cambridge, MA
National Research and Resource Facility for Submicron Structures, Cornell University	University-based consortium	Ithaca, NY
Microelectronics Center of North Carolina	Quasi-independent institute	Research Triangle Park, NC

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

participants surveyed, the results described in this chapter should be considered suggestive rather than definitive. However, it should also be recognized that data from the three surveys are consistent with one another, and the conclusions drawn therefrom are supported by independent studies. The following is a summary of the survey results.

Program Scope and Organization

As a survey group, the Federal laboratory programs, which are particularly important in advanced materials R&D, are considerably larger and better established than the other research-performing organizations in the sample. The Federal laboratory programs are staffed by large complements of full-time employees, while the university-based consortium programs generally consist of small groups of full-time staff and large numbers of part-time faculty and student affiliates.

These various organizational types also depend on different sources of funding. The Federal laboratories depend almost exclusively on Federal appropriations. The university-based consortia depend primarily on Federal grants, but also have some industry and State government support. The quasi-independent institutes tend to receive their funding from State governments and industry.

The consensus of government policymakers interviewed was that the States now have assumed an equal, if not leading role in the development of collaborative research programs.[17] Several of the respondents noted the relative advantages that States have in this area, including special knowledge about regional economies, the ability to tie R&D initiatives more closely to State-level economic planning, and the ability to control incentives such as taxation and regulation in a much more targeted manner. As one policymaker

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[17] A review of State and local programs aimed at promoting regional economic development may be found in another OTA report entitled *Technology, Innovation, and Regional Economic Development*, OTA-STI-238 (Washington, DC: U.S. Government Printing Office, July 1984).

Table 10-4.—Industry Participants and Government Policymakers Surveyed by OTA

Industry participants:

1. Allegheny-Ludlum Corp.
2. Aluminum Co. of America
3. Arco Chemical Co.
4. Bell-Northern Research Ltd.
5. Boeing Commercial Airplane Co.
6. Corning Glass Works
7. E.I. du Pont de Nemours & Co.
8. General Motors Corp. Technology Center
9. Goodyear Tire & Rubber Co.
10. Hewlett-Packard Co.
11. Honeywell, Inc.
12. Johnson & Johnson
13. Martin Marietta Corp.
14. McDonnell Douglas Corp.
15. MIPS Computer Systems
16. Noranda, Inc.
17. Shipley Co., Inc.
18. TRW, Inc.
19. Upjohn Co.

Government policymakers:

State-level administrators of collaborative programs (2)
Federal policy researchers (2)
Federal administrators of collaborative R&D programs (2)
Congressional policy analysts (2)
Member of White House science policy staff

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

noted, it is a "finite universe at the State level," and the limited number of stakeholders permits a "type of flexibility impossible for the Federal Government."

On the other hand, the government policymakers saw a continued and important role for the Federal Government in developing and supporting collaborative programs in which the major emphasis is on fundamental science. Some felt that because the Federal Government is not hampered by provincial (and perhaps competitive) State economic interests, it is capable of developing and siting such programs in a more objective way. However, there were strong opinions expressed about the need for State/Federal collaborative planning in future initiatives. Respondents felt that there was a strong possibility—and some existing cases—in which Federal programs and State programs were duplicative. At the least, they felt that the Federal Government has an obligation to consult with State-level technology planners before siting a major facility in a State.

Industry Involvement

In general, the R&D programs covered by the OTA surveys do not involve intense, bench-level interaction between research staff and industry collaborators. In many programs, the nature of the collaboration is more symbolic, and written reports or special seminars are the most common methods for disseminating research results. Thus, use of the word "collaboration" may be misleading in describing these programs.[18]

Industry respondents were asked about their companies' involvement in strategic planning, project selection, and project monitoring. Their responses showed only a moderate degree of involvement, with no significant differences across technology areas.[19]

Virtually all of the government policymakers interviewed saw industry's limited involvement in collaborative programs as a continuing problem for which there is no quick or easy solution. They felt that while a number of specific mechanisms and approaches could be used, the level of industry involvement would depend on good person-to-person contact at the technical level. Suggestions included sabbaticals for industry personnel to spend time at research organizations, and vice versa. Also mentioned was involving people other than scientists (e.g., managers or production personnel) from the participating companies. However, some respondents cautioned that extensive involvement of industrial personnel or university personnel in sabbatical exchanges might be hampered by the career disincentives arising from being absent from one's regular position for an extended period of time.

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[18] The extent of industry participation appears to be greater in the context of one-on-one, project-specific cooperation between a company and a university, as compared with multicompany, multiproject centers. See, for example, Denis Gray, Elmima Johnson, and Teresa Gidley, "Industry-University Projects in Centers: An Empirical Comparison of Two Federally Funded Models of Cooperative Science," *Evaluation Review*, December 1987.

[19] A graphic example of the isolation of industry participants from the communication network of industry/university collaborative centers may be found in J.D. Eveland, "Communication Networks in University/Industry Cooperative Research Centers," (Washington, DC: Division of Industrial Science and Technological Innovation, National Science Foundation, 1985).

Intellectual Property

Both university-based consortia and Federal laboratories tend to have similar policies on patent ownership. The most common pattern is for research-performing organizations to retain intellectual property rights to the work and to grant nonexclusive licenses to industry participants. In a minority of cases, the organizations are able to grant exclusive intellectual property rights to industry participants.

However, there were some subtle differences in how patent policies were administered and implemented. Overall, access to intellectual property by industry partners seems easier in university programs. One industry respondent noted:

> The Department of Energy's procedures are incredibly slow and ineffective. They almost never give exclusive licenses to technology—so it's hard for firms to pick up patents.

And as one Federal laboratory director put it:

> The time and hassle involved for a firm in working with us is a major impediment to doing industrial research . . . and because industry wants clear titles granted or exclusive licenses from any resulting technology, they figure, "Why collaborate?"

There is some survey evidence of informal skirting of the bureaucratic procedures at Federal laboratories. As one respondent noted:

> Most exchange of information is based on "technical intelligence," not patents. Most commercialization takes place through informal, old-boy networks. People hear about things . . . come for visits, talk to staff, very little [happens] through formal channels, such as patent transfer.

The Federal Technology Transfer Act of 1986 (Public Law 99-502) has made it possible for government laboratories to grant exclusive licenses to industry for technologies resulting from joint R&D. Industry and government sources contacted by OTA were in agreement that the legislation now in place clears the way for effective collaboration. The questions remaining are how the legislation will be implemented at the laboratory level, and how quickly the culture of the laboratories will change to address industry needs.

Proprietary Research

Among the survey respondents, there is a mixture of practices relating to how proprietary work is handled by the research staff. In some programs, no proprietary work is done by members of the staff. However, roughly 40 percent of the programs permit staff to conduct proprietary work using the same equipment and facilities, but that work is done "outside" the program—typically through a one-on-one consulting contract. In three programs, proprietary work is not only done by the program personnel but it is a legitimate and visible part of the organization's formal efforts.

One interesting development, seen particularly in the biotechnology area, and to a lesser extent in the advanced materials area, is what may be termed a hybrid program; i.e., one portion of the overall program agenda is dedicated to basic or applied research of a nonproprietary nature, while parallel, proprietary work is also done on a project-specific basis, but still within the overall program scope.

For instance, one respondent described a two-tiered research program in the advanced materials area. The research-performing organization engages in generic research but also takes on contracts with individual companies. There tends to be a great deal of interaction between university researchers and industry scientists in both tiers. In the contract projects, the company retains exclusive patent rights, but the research-performing organization retains the right to publish the results stemming from the projects, often after a built-in period of delay. For the most part, the hybrids exist as new State government/university initiatives, often closely tied to economic development planning.

The one clear area of difference between university- and Federal laboratory-based collaborative programs lies in the ability of staff to do proprietary work for or with industry partners. Virtually all of the university respondents in the advanced materials area indicated that proprietary work is undertaken. In a few cases, this is done as part of an official program, most often through one-on-one contracts and consulting agreements.

The situation in the Federal laboratories is quite different. All of the Federal laboratory respondents indicated that proprietary work is rare at best. The inability, prior to the Federal Technology Transfer Act, of firms to get nondisclosure agreements regarding collaborative research results was seen as the primary barrier to collaboration.

A majority of the policymakers interviewed felt that the legitimation of proprietary work in the collaborative programs is essential for accelerating the commercialization of research results. One respondent noted that it is "impossible to pursue commercialization without doing proprietary work." Unless researchers and research teams can continue the thrust of basic work into more dedicated applications for individual companies, observed the policymakers, promising findings would not be followed through. Nonetheless, they also felt that proprietary work should not be the primary or exclusive mission of publicly supported research-performing organizations.

The policymaker respondents offered a variety of specific solutions as to how proprietary work could be conducted in the context of collaborative programs. The common element in these solutions was the notion of establishing a parallel structure: the basic or generic research program would constitute the core thrust of the research-performing organization, with other dedicated projects being conducted simultaneously for individual companies.

The policymakers suggested various organizational solutions for achieving parallel structures. One was to set up for-profit subsidiaries. Another was to set up a campus-based but legally independent institution which could pursue product development as a follow-on to research from the core program. The overall feeling among the respondents was that it is not difficult to figure out a way to perform proprietary work. In the words of one policymaker, "People seem to be able to juggle these things."

Although the policymakers presented a generally positive attitude toward proprietary research, some noted that there are several university administrators and scientists who are concerned that doing such work will harm the traditional culture of the university.[20] They also suggested that there are significant differences across research-performing organizations (particularly universities) in the cultural values or sense of mission supporting proprietary work. One implication for policymakers would be to locate collaborative programs in institutions that perceive industry-oriented research to be part of their overall mission, rather than in institutions that have little or no interest in such research.

Participation by Foreign Companies

Because of concerns about losing the competitive edge in key technologies, the participation of foreign companies in U.S. collaborative R&D programs remains a thorny issue. In the advanced materials area, university-based consortia generally have foreign companies as members, whereas Federal laboratories work only with U.S. companies. This issue becomes even more complicated as advanced materials companies become more multinational.

All of the policymaker respondents viewed foreign participation as a highly sensitive and important issue. However, none argued for a more restrictive approach to foreign access to U.S. research. The general feeling was that the Nation would lose more than it would gain through more restrictive policies, and that such a policy would not address the true underlying problem: U.S. companies are not effectively using the research results coming out of collaborative R&D programs, particularly those based in the Federal laboratories.

The respondents noted that U.S. companies have not adopted the aggressive pursuit of external information practiced by foreign companies, and have not been willing to assign their best scientific personnel to participate in collaborative research programs. As one respondent declared: "The challenge is not to restrict access, but to run faster."

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[20] The effects of industrial support on academic researchers in biotechnology are reviewed in David Blumenthal, et al., "University-Industry Research Relationships in Biotechnology: Implications for the University," *Science*, June 13, 1986.

The respondents also discussed the need for "parity" or "equity" in scientific exchanges, which would enable U.S. institutions to obtain as much quality scientific information as they give out. The respondents felt this principle should also guide personnel exchanges and site visit access.[21]

A few respondents suggested providing a preferential approach to the dissemination of research results to U.S. companies, to give them an advantage over foreign competitors. For instance, one respondent suggested that U.S. companies, or member companies in collaborative program consortia, be given early versions of unpublished results. Another suggested that foreign clients or companies should pay a premium to obtain research results or reports from such programs.

Collaborative Program Goals

Goals of Research-Performing Organizations and Their Industry Partners

In surveying research-performing organizations, OTA asked managers to assess the relative importance of various program goals on a scale of 1 to 4. A summary of their answers is given in table 10-5, organized by technical area.

There was a consensus across the technical areas in the priority and ranking given to the various goals. Generally speaking, high marks were given to such goals as expanding the knowledge base, transferring knowledge, enhancing training, and fostering different types of industry research. Goals such as patents or commercialized products were not ranked highly, although there was considerable variance.

Similarly, OTA asked the industry participants to rank their goals and motives for affiliating with the collaborative centers. The answers are also given in table 10-5 so they can be compared with those of the research managers. As can be seen, the results closely parallel one another, indicating convergence between the two groups on program goals and expectations. Most highly ranked by both were the general expansion of knowledge as well as the transfer of basic scientific information between collaborative partners. Although the industry participants ranked goals such as patents and commercial products somewhat higher than R&D managers in the research-performing organizations, these goals do not appear to be the principal motivating force behind the collaboration.[22]

Responses to related survey questions provided further insight into the collaborative relationship. The industry participants were asked how affiliation with research programs complemented their own companies' activities. The most frequent comments centered around the idea that affiliation is a way for the company to acquire knowledge. As one respondent noted,

> When we started we had no experience in this area. The program provided a window on potential areas of advanced materials in the future.

It is important to note that in large measure the industry participants did not gain such knowledge through reading reports. Rather, they valued in particular the access to knowledgeable people—both faculty and graduate students. The respondents also were asked about their primary motivation for corporate affiliation with collaborative R&D programs. Comments received most often included "technical expertise," the organization being a "leader in a specific technology process," and the desire to "maintain and facilitate a window on developments . . . especially work being done at the best U.S. universities."

Access to graduate students was a significant motivator for some companies, particularly in the

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[21] The principle that the United States and Japan should have "symmetrical access" to each other's science and technology institutions was advanced at the Second U.S.-Japan Conference on High Technology and the International Environment, a meeting jointly sponsored by the U.S. National Academies of Sciences and Engineering and the Japan Society for the Promotion of Science, held in Kyoto, Japan, Nov. 9-11, 1986.

[22] These results for organizations based on the university consortium model are consistent with those of previous studies: see Denis Gray and Teresa Gidley, "Evaluation of the NSF University/Industry Cooperative Research Centers: Descriptive and Correlative Findings from the 1983 Structure/Outcome Surveys," unpublished paper, Department of Psychology and Center for Communications and Signal Processing, North Carolina State University, Raleigh, NC, June 1986; Gray, Johnson, and Gidley, op. cit., see footnote 18, 1987; Mike Devine, Tom James, and Tim Adams, "Government Supported University/Industry Research Centers: Issues for Successful Technology Transfer," paper presented at the Twelfth Annual Meeting and International Symposium of the Technology Transfer Society, Washington, DC, June 23-25, 1987.

Table 10-5.—Relative Importance of Collaborative Program Goals Identified by Industry Participants (IP) and Research Managers (RM) by Technical Area[a]

	Advanced materials		Information technology		Biotechnology	
Goal	IP	RM	IP	RM	IP	RM
General expansion of knowledge	3.4	3.7	4.0	4.0	2.8	3.8
Transferring knowledge between collaborative partners	3.2	3.6	3.0	4.0	3.2	3.8
Enhancement of training for research personnel	2.8	3.0	3.7	3.8	2.8	3.0
Enhancement of industrial research	3.1	2.8	2.0	3.0	3.0	2.5
Redirection of university research	2.5	2.6	2.0	2.0	2.8	1.0
Development of new research projects with collaborating firms	2.9	2.1	2.0	2.5	3.0	2.3
Development of patentable products	2.4	2.5	1.0	1.5	3.0	3.0
Development of commercialized products	3.1	2.2	2.0	1.5	3.0	2.8

[a] Scores could range from 1 to 4 with 4 being the highest in importance. Entries are mean scores.

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

information technology area. Research-performing organizations are seen by some industry participants as being akin to "intellectual feed lots" for the nurturing of future personnel. Some respondents mentioned that access to particular facilities, unavailable in their own companies, was another motivating force for affiliation.

Overall, the industry participants' reasons for corporate affiliation with research-performing organizations are best summed up by one respondent:

> The specific projects are not as important. People in charge are too far removed from the realities of product and market development. It's not their bag, and we don't expect them to do it. They rejuvenate our bag of tricks; we take it to the marketplace.

Commercialization as Mission

Typically, the research managers interviewed by OTA cited three reasons for establishing collaborative R&D programs: 1) response to a funding opportunity or an opportunity to establish stability of funding, 2) response to industry needs or to a larger economic agenda, or 3) response to the fulfillment of a government agency mission.

Programs that were founded to address industry needs or economic development concerns were able to identify more in the way of commercial results. This observation, of course, merely reflects that an organization that plans from the beginning for a certain outcome is more likely to achieve it. However, it also reflects distinct differences in the way these organizations engaged in collaborative programs approach their missions. For instance, one academic respondent whose organization reported few commercial outcomes stated that it would be "repugnant" to consider commercialization as a factor in how research reports are disseminated. By contrast, a peer in the same technical area, when questioned about project monitoring, noted that "one of the things we look at when we review projects . . . is whether something is patentable."

Another respondent at a Federal laboratory noted that strategic planning was approached with the idea that commercialization was a "real gold star." In the biotechnology area, when asked about the strategic planning function, one respondent stated,

> We don't want to overlook the science, but the thrust of our activities is the enhancement of economic development through information and technology transfer . . . Essentially everything being done in the program has some commercial potential.

These comments capture the more pervasive sense of commercialization as mission in some research-performing organizations. This mission would seem to be established early and is probably woven into the very fabric of the organization. There appear to be some differences in commercialization perspective across technical areas, though. The newer biotechnology centers appeared to be significantly more oriented toward commercialization as "embedded mission" than is the case with the more established centers in the other technologies.

There was considerable disagreement among the policymakers on the extent to which research-performing organizations should adopt a full-blown commercialization perspective in their operations. Two of the respondents argued that some collaborative research organizations, particularly universities, will always be oriented primarily toward fundamental science. Moreover, they argued, this is appropriate and desirable, given the historical mission of university research. On the other hand, the other respondents suggested that a commercialization perspective ought to be built into research organizations, but they differed as to how to accomplish this objective.

Several of the policymakers suggested that the hybrid programs represent a desirable option. Virtually all the policymakers suggested that the adoption of a more aggressive commercialization perspective would be enhanced by facilitating a greater mingling across the stakeholder groups; i.e., through greater use of joint staff/industry committees to set the research agendas, increased emphasis on personnel exchanges, and informal interactions among the different stakeholder groups.

Industry Capacity and Incentives for Commercialization

Only about half of the surveyed industry participants who are affiliated with advanced materials research-performing organizations reported any internal follow-on work initiated as a result of collaboration. Given that the organizations had identified the surveyed industry participants as their most active collaborators, this proportion is likely to be an overestimate of follow-on activities on a nationwide basis.

Obstacles to Commercialization

To further explore the industry respondents' views on the commercialization process, OTA asked them to rate several potential obstacles to this process. These included such issues as the management of the collaborative program, skill levels of company technical personnel, interdisciplinary content of the new technologies, manufacturing scale-up costs, market uncertainties, cost justification, government policies, the planning process, and the lack of integration between the design and manufacturing functions. Each factor was rated on a 4-point scale, with 1 representing no obstacle at all and 4 representing a significant obstacle to commercialization.

In addition, the respondents were given the opportunity to identify other obstacles, as well as to elaborate on why they felt some factors were more important than others. They were also asked whether the institutional arrangements between their companies and the collaborative research-performing organizations constituted a significant obstacle.

Table 10-6 presents the summary data on obstacles to commercialization, as ranked in importance by industry participants and organized by technical area. Over the three technologies, the cost to scale-up manufacturing processes was the most significant obstacle, closely followed by market uncertainties and difficulties in the cost justification of new technologies. In the opinion of the respondents, advanced materials technologies are particularly beset by a cluster of problems centering on economics. There are major market uncertainties in the advanced materials area, which, coupled with high scale-up costs, create significant cost justification problems.

The issues of market uncertainty, planning, and cost justification tended to be intertwined in the perceptions of the respondents. The following three comments are illustrative:

> If we develop something that looks real good, but has never been commercialized and it takes a big chunk of capital . . . it's a very tough decision.

> This contrasts to the costing of products and their justification, where the product and market are known, and payback comes in a few years. The entire management chain is conditioned to this, and R&D programs tend to be funded through product line management.

Table 10-6.—Relative Importance of Obstacles to Commercialization Identified by Industrial Participants by Technical Area[a]

Obstacle	Advanced materials	Information technology	Biotechnology	Overall
Management of collaborative program	1.4	1.7	1.0	1.4
Level of technical training in company	1.9	2.0	1.6	1.8
Cost to scale-up manufacturing	3.2	3.3	2.4	3.0
Market uncertainties	3.3	2.0	2.2	2.8
Interdisciplinary nature of R&D	1.9	2.0	1.4	1.8
Cost justification	3.2	2.7	2.0	2.8
Government policies	2.3	1.7	3.0	2.4
Short-term planning	2.6	3.0	2.2	2.6
Lack of integration between design and manufacturing	3.0	2.3	2.4	2.7

[a] Scores could range from 1 to 4 with 4 being the highest in importance. Entries are mean sources.

SOURCE: Louis G. Tornatzky, Trudy S. Solomon, and J.D. Eveland, "Examining Collaborative Agreements in Advanced Materials and Other High Technology Fields," contractor report for OTA, February 1987.

> To the extent that you are directly replacing a product with a new one, this is not a problem . . . New products or applications are the problem.

Only in the biotechnology area were government policies seen as the greatest obstacle to commercialization. Concerns expressed by respondents focused on the intensity of environmental and safety pressures and the overlap between Federal and State regulations.

The industry respondents offered several partial solutions to these obstacles to commercialization. In the advanced materials area, some suggested approaches centered on temporarily suspending a market-pull philosophy and moving toward a more aggressive technology-push approach. One respondent suggested that industry should: ". . . invest money, make product, and create a market. We do it backwards."

Some suggested that the present market in advanced materials is insufficient to warrant major investments in commercialization, given the traditional approaches to cost justification. Some suggested a more systemic long-term approach to product planning and development. Some suggested that the government should play a role, perhaps with some tax incentives to "encourage risk capital to go after new processes." Some pointed out that such countries as Japan are developing ceramics without an obvious current market need. (These comments echo the themes presented in chs. 8 and 9.)

In assessing the industry participants' views on commercialization obstacles, all survey respondents were asked whether changes in the institutional arrangements between their companies and research-performing organizations would help. By a large majority (82 percent), they indicated that this was not the case. Rather, they perceived the obstacles as emanating from their own companies.

Several policymakers pointed out the lack of a technology infrastructure to enable promising research results to move across the boundaries between research-performing organizations and their industry clients. They suggested that the level of industry involvement in these organizations be increased, and especially that it be expanded to include individuals who represent different levels and functions within the industry organization, including those from manufacturing and product development, as well as R&D. As one respondent noted:

> People in industry in a position to commercialize results, whose job it is to do it, are not in communication with those with the data in these programs.

CONCLUSION

The capability of collaborative R&D arrangements to enhance the competitiveness of U.S. industry depends on several interrelated factors: the institutional structure of the collaborative program, the type of technology involved, and the economic incentives for commercializing that technology.

In assessing the effectiveness of collaborations in bridging the gap between basic research and commercial products, a distinction must be made between the technology transfer process and the driving force behind the transfer. When the economic driving force is present, the institutional arrangements can have a significant impact on the pace of commercialization. For instance, experience suggests that hybrid programs featuring opportunities for proprietary, project-specific research as well as nonproprietary, generic research lead to greater commercialization than do those featuring generic research alone.

However, if the economic driving force is not present, specific institutional arrangements are not likely to make much difference. In the case of advanced materials, a significant gap still remains between the point at which collaborative work leaves off and that at which industry commitment begins. This is largely due to economic factors, especially the high cost of manufacturing scale-up in an uncertain business climate. Thus, while collaborative programs of the type surveyed by OTA do provide valuable products in the form of trained students and new research results, these surveys suggest that the programs should not be viewed as solutions to the problem of relatively slow commercialization of advanced materials in the United States. Options for addressing this problem are discussed further in chapter 12.

APPENDIX 10-1: METHODOLOGY

The purpose of the OTA surveys was to provide a basis for an analytical description of collaborative R&D activities in advanced materials, and to draw lessons where appropriate from similar activities in biotechnology and information technology. The particular focus was on research-performing organizations that have significant government support, either from Federal or State funding programs, and that have collaborative arrangements with industrial firms operating in the same technology area. The primary analytic question was, "What impacts do collaborative research programs have on the translation of basic research into commercial products in these technical areas?"

OTA used a methodology intended to "triangulate" a set of results. Primary data and other information were collected from three sources: research-performing organizations, companies that are the clients and collaborators of the research-performing organizations, and former and current government policymakers at the Federal and State level who are familiar with the context in which the collaborative arrangements have been established and managed.

Data collection and analysis were driven by a set of 10 major issues, formulated as follows:

1. What is the evolutionary history of collaborative R&D in terms of stakeholder involvement, initial premises and mission, funding support, and growth? Are these founding issues related to involvement in and success with the commercialization experiences of industry partners?
2. To what extent are industry participants involved at both a policy and management level in the ongoing operations of research-performing organizations? Is this involvement related to an increased level of interaction or commercialization by industry partners, and what are the ways in which programs can become more collaborative?
3. To what extent do commercialization issues influence the policies and practices of research-performing organizations, and how can collaborative R&D programs be made more responsive to the goal of commercialization?
4. What has been the experience and success of industry partners' commercialization of results emanating from collaborative R&D programs, and how does this differ across different types of research-performing organizations and the three technical areas under study?
5. What is the nature of work being done collaboratively with the research-performing or-

ganizations, and to what extent has this work contributed to follow-on R&D by the industry participants or to commercial products and processes?

6. What are the primary obstacles to commercialization in the three technical areas from the perspective of industry participants?
7. How should publicly supported collaborative R&D programs resolve the issue of doing proprietary work for industry participants?
8. Are any programmatic changes needed in the area of intellectual property and patents?
9. What can be done to improve the industry participants' utilization of research results stemming from these collaborative programs?
10. What are the appropriate roles of Federal and State governments in the future design, funding, and operation of collaborative R&D programs?

Selection of Survey Participants

Survey of Research-Performing Organizations

Several key criteria were used by OTA in selecting organizations to participate in the survey of research-performing organizations. The survey was confined to distinct organizational entities, such as institutes or centers, that were engaged in several discrete projects. Organizations were selected that had significant fiscal, intellectual, or contractual involvement with one or more industrial firms, that were judged to be technologically in the upper tier of their field, and that had an experience record of at least 2 to 3 years of operation.

Initially, 22 candidate organizations were identified and contacted. Of these, 3 declined to participate. The final sample of 19 research-performing organizations consisted of 11 in the advanced materials area (including 5 Federal laboratories), 4 in biotechnology, and 4 in information technology. The typical survey respondent in each of the organizations was a program administrator and/or senior scientist. A list of participating organizations is given in table 10-3.

Industrial Participants Survey

As part of the survey of research-performing organizations, respondents at each of the 19 organizations that participated were asked to identify at least two individuals from industry who had a significant ongoing relationship with his or her program. Of these 19 respondents, 2 declined to identify industry personnel, and 2 identified only a single contact each, yielding a potential sample of 32 industry participants. Of these, 10 could not be contacted during the time period for data collection and 3 declined to participate, leaving a final sample of 19 individuals.

The job categories of the industry participants were relatively homogeneous. Of the 19 respondents, 12 functioned as research managers and 7 performed in a business management capacity. A list of the companies represented in the survey is given in table 10-4.

Survey of Government Policymakers

Information was gathered through telephone interviews with nine respondents. Respondents were chosen to reflect a variety of sectors and viewpoints: two State-level administrators of collaborative R&D programs; two policy researchers; two current or former administrators of collaborative R&D programs; two congressional policy analysts; and one current member of the White House science policy staff. The sample was constructed so as to provide a broad-based evaluation of—and expansion on—findings from the other two surveys.

Survey Data and Analysis

For each of the three surveys, an interview protocol was developed consisting of both short-answer and open-ended questions grouped according to the 10 major issue areas described above. The interviews, which lasted from 30 to 90 minutes, yielded a mixture of qualitative and quantitative information, supplemented by written background material supplied by the interviewees. For the qualitative information, a master coding protocol was used to convert the data to nominal (yes/no) form suitable for descriptive statistics. In the survey of policymakers, no formal content analysis procedures were employed; the intent was to capture recurrent themes contained in the interviews rather than to generate quantitative or quasi-quantitative data.

Statistical treatment of the data was primarily descriptive in nature. Some comparative analyses were also performed. The small sizes of the samples precluded more sophisticated analysis. Data presented in the tables in the body of this chapter should be considered as useful abstractions of an essentially qualitative analysis rather than as quantitative or rigorous.

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The Military Role in Advanced Materials Development

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Chapter 11

The Military Role in Advanced Materials Development

FINDINGS

The military sponsors about 60 percent (roughly $98 million of $167 million in 1987) of Federal advanced structural ceramics and composites research and development in the United States. These figures do not include the additional R&D funded in classified programs and in other categories of materials research such as engineering development and operational systems development. The military establishment continues to provide the major U.S. market for advanced materials. However, military markets alone are not large enough to sustain a viable advanced materials industry.

Military advanced materials R&D investments could make a significant contribution to the competitiveness of U.S. firms. However, military and commercial interests in these materials differ. As commercial markets for these materials continue to grow, balancing military and commercial interests in advanced materials could become a critical factor in U.S. competitiveness. Among the major issues that will require resolution are export controls, controls on information, offsets, and government procurement practices.

Advanced materials are used in military systems, whose export is controlled by the Department of State, and in "dual use" products (those with both military and commercial application), whose export is controlled by the Department of Commerce. For national security reasons, the Department of Defense (DoD) also has a major influence on export control decisions.

Export controls, although necessary for national security reasons, are considered by U.S. industry to be cumbersome and outdated. Delays in processing export licenses can result in loss of sales abroad. Export control procedures relating to metal matrix composites (MMCs) are especially confusing, and it is not clear to U.S. MMC suppliers interviewed by OTA which Federal agency has the responsibility for controlling these materials. Commercial industry representation in export control policymaking bodies is minimal. Greater representation by commercially-oriented industry could help to provide a balance between military and commercial interests in export control policy.

Via an informal international agreement, the United States, all of the other NATO countries (except Iceland), and Japan have established an export control organization called the Coordinating Committee for Export Controls, or, informally, CoCom. This organization informally maintains multilateral controls on certain technologies that have been agreed upon by all member nations.

Export controls are intended to prevent direct shipment of militarily significant technologies to proscribed countries. Because U.S. technology exported to an approved country can often then be reexported to a proscribed country, the United States also maintains reexport controls. These reexport controls generally involve a requirement that a foreign company wishing to reexport technology received from the United States must apply to the United States for a license. Many countries view U.S. reexport controls as unwarranted interference in their political and commercial affairs, and in some cases these controls have been detrimental to U.S. trade as well as to relations with allied nations. The United States is the only country that seeks to control the reexport of information and products in a significant way.

Technical information about advanced materials is currently controlled under a complex regime of laws and regulations administered by the Departments of State, Commerce, and Defense. These controls can be confusing to the advanced materials community and tend to limit the transfer of military materials technology to the commercial sector. Some of the controls are intended to prevent non-U.S. citizens from receiving information; these policies are increasingly coming into conflict with the internationalization of the advanced materials industries. Such policies run the risk of provoking retaliatory restrictions on the flow of technical information into the United States. This could prove detrimental to the rate of technology development in the United States, especially in cases where superior technology exists abroad.

Although not strictly a military issue, controlled or proprietary information about advanced materials may be distributed worldwide by the practice of offsets. Offsets are the offering of credits toward the acquisition of supporting technology to ensure sale of U.S. military systems (e.g., aircraft) to a foreign government. This newly acquired technology subsequently enables foreign companies to compete with the United States in the production of future military systems. Offsets are an integral part of the complex foreign policy considerations that go into such sales. Although offsets are reviewed for national security reasons, they receive no economic review for potential harm to the U.S. industrial base.

As with other technologies, such as microelectronics and machine tools, there is a growing recognition within DoD of the importance of maintaining a strong domestic manufacturing capacity for advanced materials. To fulfill its goals of supporting the U.S. industrial base, DoD has been developing a plan to pursue domestic production of some types of advanced materials regarded as critical, particularly polyacrylonitrile (PAN) fiber precursor for polymer matrix composites (PMCs). The Department of Defense Appropriations Act of 1987 (Public Law 100-202) requires that 50 percent of all PAN precursor used in U.S. military systems must be domestically produced by 1992. This legislation includes a timetable and incremental goals for achieving this level of domestic production. As yet DoD has not completed a plan for implementing the domestic PAN production requirements, causing uncertainty within industry regarding plant location and capacity, establishment of foreign-owned plants in the United States, and materials qualification.

INTRODUCTION

At present, the military is one of the largest customers for advanced materials, especially PMCs. DoD has committed to purchase 80 billion dollars worth of weapons systems that use various types of advanced composites.[1] DoD funding for basic research and exploratory development in advanced structural materials constitutes about 60 percent of total Federal R&D expenditures for these materials, as shown in table 11-1.

Composites are used in many military applications by all three services. The Army is pursuing PMCs and ceramic matrix composites (CMCs) for body and vehicle armor.[2] In addition, MMCs are being considered for use by the Navy and Air Force for structural components of aircraft, missiles, torpedoes, and other weapons systems components.[3]

In the past, PMCs have been used in the Army's Apache and Black Hawk helicopters, Navy aircraft such as the F-14, the FA-18, the AV-8B, and the Air Force's F-15 and F-16. With the experience gained in military applications such as fighter aircraft and rocket motor casings beginning in the 1970s, PMCs now have a solid record of performance and reliability, and are rapidly becoming baseline structural materials in the defense/aerospace industry.[4] In the future, military investment in composite materials is expected to grow rapidly. Composites will be enabling technologies for new programs such as the National Aerospace Plane.

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[1] Kenneth Foster, U.S. Department of Defense, personal communication, June 1987.

[2] U.S. Department of Defense, Standardization Program Plan, Composites Technology Program Area (CMPS), Mar. 13, 1987.

[3] Ibid.

[4] Suppliers of Advanced Composite Materials Association, Annual Meeting and Industry Conference, May 5-8, 1987.

Table 11-1.—U.S. Government Agency Funding for Advanced Structural Materials in Fiscal Year 1987 (millions of dollars)

Agency	Ceramics and ceramic matrix composites	Polymer matrix composites	Metal matrix composites	Carbon/carbon composites	Total
Department of Defense[a]	$21.5	$33.8	$29.7	$13.2	$ 98.2
Department of Energy	36.0	—	—	—	36.0
National Aeronautics and Space Administration	7.0	5.0	5.6	2.1	19.7
National Science Foundation	3.7	3.0	—	—	6.7
National Bureau of Standards	3.0	0.5	1.0	—	4.5
Bureau of Mines	2.0	—	—	—	2.0
Department of Transportation	—	0.2	—	—	0.2
Total	$73.2	$42.5	$36.3	$15.3	$167.3

[a] Includes only budget categories 6.1-6.3A.

SOURCE: OTA survey of agency representatives.

PMCs are under consideration for several systems including the Navy's V-22 Osprey (at this writing in prototype production using PMCs), the Army's LHX helicopters,[5] and the Air Force's Advanced Tactical Fighter (ATF).[6] [7] Military research in PMCs has aimed at achieving higher operating temperatures, higher toughness, lower radar observability, and reduced weight, among other goals. For these reasons, military policies and regulations will continue to have a major effect on the future of these materials as they start to be used more commercially.

Although DoD provides the major market for U.S. advanced material suppliers, DoD policies and methods can conflict with industry goals and preferences regarding the development of advanced materials. One source of conflict is that between national security interests and economic needs in terms of foreign trade in advanced materials. The conflict arises because such materials are a critical element in many new weapons systems, hence the military prefers to restrict their availability; at the same time though, these materials, through their potential use in a wide variety of civilian manufactured products, could play a valuable role in U.S. economic development and international trade.

A second source of conflict lies in how defense systems are procured by the Federal Government. DoD has two primary goals relating to procurement: securing a reliable domestic technology base, and having the widest spectrum of technologies available at the lowest possible cost. To achieve these goals, DoD employs a variety of incentives and regulations in its procurement programs. Participation by industry in these programs is more dependent on these DoD policies than on conventional economic criteria.[8]

Military advanced materials R&D investments could make a significant contribution to the competitiveness of U.S. firms. However, several controversial issues need to be addressed in order to make this contribution more effective. These include: export and reexport controls on products and technical information, access to data on materials, and materials procurement policies.

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[5] The Army has recently restructured the LHX program; the restructuring plan is pending the approval of the Defense Acquisition Board. Brendan M. Greeley, Jr., "Army to Award Parallel Contracts for Revised Development of LHX," *Aviation Week and Space Technology*, Mar. 14, 1988, p. 247.

[6] Composite News, *Advanced Composites*, January/February 1987.

[7] "Materials Pace ATF Design," *Aerospace America*, Apr. 1987, pp. 16-22.

[8] Technology Management Associates, "Industrial Criteria for Investment Decisions in R&D and Production Facilities," OTA contractor report, Jan. 28, 1987.

EXPORT CONTROLS

U.S. export control policies have been recently reviewed in the context of balancing national security and economic development goals.[9] Advanced materials technologies are considered to be "dual-use" technologies (as are, for instance, microelectronics or machine tools) because they have both civilian and military applications. As such, they are subject to U.S. export controls. Accordingly, the U.S. export control regime is an important factor in the present and future development of advanced materials in the United States.

U.S. Export Control Regime

Export of advanced materials products and technical information about advanced materials is currently controlled under a complex regime of laws and regulations. The Federal agencies responsible for export control are listed in table 11-2. Export control responsibility lies by law[10] primarily with the Departments of Commerce and State. DoD influences the policymaking of these departments and has power of refusal over export license applications, but has no export control authority of its own, as mandated by the Export Administration Act of 1979 (Public Law 96-72).

The Departments of Commerce and State each have their own lists of technologies that are export-controlled: the Department of Commerce administers the U.S. Commodity Control List; the

Table 11-2.—The Export Control Regime

U.S. agency	Controls	Regulations	Technology list
Department of Commerce (International Trade Administration)	Dual-use technologies	Export Administration Regulations (EAR)	U.S. Commodity Control List
Department of State (Office of Munitions Control)	Defense articles, defense services, and related technical data	International Traffic in Arms Regulations (ITAR)	U.S. Munitions List
Department of Defense	Advisory only	Guidelines only	Militarily Critical Technologies List (MCTL)
International (CoCom)			
NATO countries except Iceland, plus Japan	Dual-use technologies [Arms] [Atomic Energy]	None, Nontreaty Agreement	International Commodity Control List, or CoCom International List
Other U.S. Agencies	*Role*		
Department of the Treasury (U.S. Customs)	Enforcement		
Department of Justice	Enforcement		
Department of Energy	Nuclear Energy and Weapons Technologies		
Nuclear Regulatory Commission	Nuclear Energy and Weapons Technologies		
NASA, Intelligence Agencies	Advisory		
National Security Council	Advisory, Dispute Resolution		

NOTE: CoCom Arms and Atomic Energy controls are similar to U.S. Department of State and U.S. Department of Energy controls, respectively.

SOURCE: National Academy of Sciences, "Balancing the National Interest," 1987.

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[9] National Academy of Sciences, *Balancing the National Interest: U.S. National Security Export Controls and Global Economic Competition*, (Washington, DC, National Academy Press, 1987).

[10] Export Administration Act, 1979, Public Law 96-72; Export Administration Act of 1981, Public Law 97-145; Export Administration Amendments Act, 1985, Public Law 99-64; Arms Export Control Act, 1976, Public Law 94-329.

Department of State administers the U.S. Munitions List. DoD maintains a separate list of technologies, called the Militarily Critical Technologies List (MCTL), that it uses as a guideline on export control matters. Congress originally mandated in 1979 that DoD develop the MCTL to be a guideline of those technologies that are critical for national defense.[11] Congress subsequently mandated in 1985 that the MCTL be merged with the U.S. Commodity Control List;[12] however, this merger has not occurred. The MCTL is currently only a guideline and has no other standing in regulation or law.

Table 11-3 describes how advanced materials are included in each of the lists. The U.S. Commodity Control List covers dual-use technologies and information, and is found at the end of the Export Administration Regulations (EAR). It has separate sections for 1) ceramics and ceramic matrix composites; 2) organic matrix materials; and 3) carbon fibers, polymer matrix composites, and metal matrix composites. Certain materials are specified in detail (e.g., polyimides, carbon fibers with certain stiffnesses and strengths), while other materials are described in a less specific way (for instance, metal matrix composites, which are described as structures or manufactures made with a metal matrix utilizing any of some specified fibrous or filamentary materials). The U.S. Com-

Table 11-3.—Export Controls on Advanced Materials

Administrative agency	Citation
Department of Commerce (EAR)	
U.S. Commodity Control List[a]	
15 CFR Ch. III	ECCN 1733A
399.1 Ceramics, ceramic matrix composites	"Base Materials, noncomposite ceramic materials, ceramic-ceramic composite materials and precursor materials for the manufacture of high temperature to high temperature fine technical ceramic products"
Organic matrix materials	ECCN 1746A "Polymeric substances and manufactures thereof" (includes polyimides, aromatic polyamides)
Carbon fibers, polymer matrix composites, metal matrix composites	ECCN 1763A "Fibrous and filamentary materials that may be used in composite structures or laminates and such composite structures or laminates"
Department of State (ITAR)	
U.S. Munitions List[a]	
22 CFR Ch. I	Category IV
121.1 Ablative materials fabricated or semifabricated from advanced composites	Launch vehicles, guided missiles, ballistic missiles, rockets, torpedos, bombs, and mines
Department of Defense	
Militarily Critical Technologies List[b]	
Part A: Arrays of Know-How	5.0 Materials and Processing Technology
Part B: Keystone Equipment	Group 3 General Industrial Equipment
Part C: Keystone Materials	ECCN #s 1733A, 1746A, 1763A
Part D: Goods Accompanied by Sophisticated Know-How	(various products and equipment)

NOTES: Export Administration Regulations (EAR) refer to some technologies in detail (PMCs, reinforcememt fibers) and other technologies in a more general manner (MMCs).
International Traffic in Arms Regulations (ITAR) refer only to ablative materials, which include MMCs.
The Militarily Critical Technologies List (MCTL) refers to a wide range of advanced materials and related technologies, and is used as a guideline for approval of licenses.

SOURCES: [a]U.S. Code of Federal Regulations, revised as of Jan. 1, 1987.
[b]U.S. Militarily Critical Technologies List (unclassified version, Oct. 1984).

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[11] Export Administration Act of 1979, Public Law 96-72.

[12] Export Administration Amendments Act of 1985, Public Law 99-64.

modity Control List also covers products and systems made from advanced materials, such as aircraft and components.

The Department of States' U.S. Munitions List covers defense articles, services, and related technical information and is found at the end of the International Traffic in Arms Regulations (ITAR). The only materials specified in this list are ablative materials (which are usually taken to include carbon/carbon and certain metal matrix composites). The Department of Defense's Militarily Critical Technologies List specifies many aspects of materials in varying degrees of technical detail, including equipment for producing these materials, some products and systems made from these materials, and technical information related to all of the above.

In some cases the responsibility for control is not clear from the lists. For instance, there is some dispute as to whether MMCs are controlled as a directly military technology under the International Traffic in Arms Regulations administered by the Department of State (U.S. Munitions List), or under the Export Administration Regulations (U.S. Commodity Control List) administered by the Department of Commerce (see box A). Normally, these two lists do not overlap in content. Except for its claim to regulate ablative materials technology, the Department of State does not regulate the export of any other advanced materials commodities or information. Because both the Department of Commerce and the Department of State send export license applications to DoD for approval, DoD has a very influential position in export controls despite the fact that it is not

Box A.—Export Control of Metal Matrix Composite Products and Information

The case of export control of MMCs provides a particularly confusing situation. The vast majority of MMC production is for military use. The Department of State has responsibility for licensing weapons and munitions and related technical data. The Department of Commerce licenses export of dual use items and related technical data. See table 11-2 for a description of the export control regime.

Both products and information related to MMCs are explicitly described in the Commodity Control List of the Department of Commerce export control regulations.[13] The Department of State's Munitions List cites "ablative materials" (usually taken to include carbon/carbon composites and certain metal matrix composites) used in such systems as launch vehicles and guided missiles. See table 11-3 for a description of advanced structural materials citations in the several export control lists.

Neither list is specific about which MMCs are controlled, and there is disagreement over which agency controls MMC information (technical data) as opposed to products. Because both agencies have regulations concerning the export of these materials, there is no one agency to which companies can routinely send all MMC export license applications. This has led to additional delays in processing of MMC export license applications.

Even after a license application has been submitted, the procedure is not clear as to whom it must be referred and which agency has final authority to issue or deny a license. This is due to the ambiguity in the technical descriptions of MMCs in the two control lists, and the overlap between Commerce and State regulations. In cases where license applications have been submitted to both agencies, contradictory responses have been received.[14]

Several actions could help alleviate this situation. Regulations regarding the control of MMCs could be rewritten to clarify which agency controls what types of MMC products and information. Both agencies should coordinate in a timely fashion to accomplish this objective. This activity could be mediated by the National Security Council. Consultations with the Materials Technical Working Group within DoD and the new Materials Technical Advisory Committee in the Department of Commerce could also help in developing regulations that are technically clear and relevant.

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[13] MMCs are found in the U.S. Commodity Control List (15 CFR 399.1, Supplement 1, Group 7), under the section on fibrous and filamentary materials, ECCN 1763A, (d).

[14] "Industrial Investment in Advanced Materials," Office of Technology Assessment workshop, Washington, DC, Dec. 15-16, 1986.

permitted by Congress to have regulatory control over exports.

There is also an informal international export control agreement between the United States, all of the other NATO countries (except Iceland), and Japan. This set of countries has established the Coordinating Committee for Export Controls, or, informally, CoCom. For over 40 years, the CoCom countries have maintained lists of technologies that they have agreed to restrict from export to proscribed country destinations. The principal such list, called the CoCom International List, is similar to the U.S. Commodity Control List of the Department of Commerce except that the U.S. list includes 27 categories of dual-use products that are not on the CoCom list.[15] In addition, there are also two CoCom lists for munitions and atomic energy that are similar to U.S. control lists for these technologies.

Effects of Export Controls

Export controls are very important to national security.[16] Proscribed countries have three options for acquiring Western defense technologies: through espionage, diversions, or through legal purchases. Export controls exist to prevent proscribed countries from directly exploiting the latter two methods. Controls on exports to friendly nations are intended to prevent diversions to proscribed countries. However, export controls are sometimes at odds with the economic objectives of the open, free-market societies of the Western allies.[17]

The main problem with the export control regime is its size and complexity. The sheer number of agencies, laws, regulations, and guidelines causes confusion for companies applying for export licenses. In fact, some companies find it necessary to hire lawyers or consultants simply for the purpose of filling out and tracking export license applications.

One of U.S. industry's main complaints about export control regulation is the time taken to process an export license application. Because advanced materials export license applications usually require interagency referral, delays are longer than average for decisions regarding these licenses (see box B). The possibility that a U.S. exporter will face long delays or will not receive a license can be enough to discourage foreign customers from buying U.S.-manufactured products.[18]

A further complaint of the industries subject to export control involves the MCTL. Presently, the ambiguous status of this list is causing confusion among these industries. The integration of the MCTL with the U.S. Commodity Control List has not yet been done and the MCTL is still nominally only a guideline. However, there have been charges that this list is being used de facto to control the export of technologies.[25] For instance, industry sources contacted by OTA consider it to be as important to amend the MCTL as the U.S. Commodity Control List.

Although export controls affect a variety of high-technology industries, there are some aspects of export control (e.g., reexport controls) that affect the advanced materials industries more severely than some other industries. This is because materials are controlled as raw and processed materials (e.g., powders, fibers), as parts and components (e.g., missile nose cones), and as subsystems (e.g., aircraft wings). At all of these stages, advanced materials are also subject to reexport controls.

Reexport Controls

The United States is the only CoCom member country that requires companies within foreign countries to request U.S. permission to reexport U.S.-made dual-use items, and foreign-made products with U.S.-made components.[26] These

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[15] National Academy of Sciences, op. cit., 1987.

[16] For a full discussion of the reasons behind export controls, see U.S. Congress, Office of Technology Assessment, *Technology and East-West Trade: An Update*," OTA-ISC-209 (Washington, DC: U.S. Government Printing Office, May 1983).

[17] National Academy of Sciences, op. cit., 1987.

[18] Technology Management Associates, "Industrial Criteria for Investment Decision in R&D and Production Facilities," contractor report prepared for the Office of Technology Assessment, Jan. 28, 1987, p. 42. See also U.S. Congress, Office of Technology Assessment, *Technology Transfer to China*," OTA-ISC-340 (Washington, DC: U.S. Government Printing Office, July 1987).

[25] National Academy of Sciences, op. cit., 1987.

[26] National Academy of Sciences, op. cit., 1987.

Box B.—Export License Application Processing

According to the Department of Commerce, the average processing time for license applications that need no interagency or CoCom referral (80 percent of cases for all information and products) is down to nine calendar days from the receipt of the application until the time the license is issued, as of December 1987.[19] The average processing time is 52 days for cases requiring referral (CoCom or interdepartmental).[20] (Usually license applications are referred to CoCom only for shipments to Communist countries.)

The Department of Commerce processed about 122,000 license applications total in fiscal year 1985, up from approximately 71,000 in fiscal year 1981.[21] In about 5 percent of the 1985 license applications, processing times were over 100 days.[22]

The Department of Commerce already has in place the System for Tracking Export License Applications (STELA), a computerized voice answering service that allows exporters to monitor the status of their license applications. DoD has a similar system, called the Export License Status Advisor, ELISA.

Early in 1987, the Department of Commerce announced reforms in the export controls that it administers.[23] New types of licenses are being made available to simplify the application procedure for a small number of exports to some of the CoCom countries. Average license application times were reduced for applications not needing referral. The Department of Commerce also proposed to loosen export restrictions on low-technology exports (e.g., personal computers) to non-CoCom countries. Parts and components regulations have also been modified.[24]

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[19] Iain Baird, U.S. Department of Commerce, personal communication, Jan. 4, 1988.

[20] Ibid.

[21] National Academy of Sciences, op. cit., 1987.

[22] Ibid.

[23] Malcolm Baldrige, *Department of Commerce News*, Feb. 9, 1987.

[24] Daniel Cook, U.S. Department of Commerce, personal communication, July 30, 1987.

reexport controls exist to make sure that products licensed for export from the United States to a particular foreign country do not end up in proscribed countries. However, many countries feel that these controls represent unwarranted interference in their political and commercial affairs.

The unilateral emphasis of the United States on reexport controls can result in a competitive disadvantage for U.S. firms. Foreign companies are concerned about potential loss of time and money involved in using U.S.-manufactured products. A reexport license application requires additional time to process here in the United States. It also requires significant effort on the part of the government of the reexporting country to make sure that those products requiring reexport control are dealt with accordingly.

In some cases, these controls have led to a process of "de-Americanization" in which foreign manufacturers avoid the use of U.S.-made products to sidestep the U.S. reexport controls. One example of de-Americanization is the barring of companies in countries requiring reexport licenses from bidding on supply contracts for the NATO fighter.[27]

For parts and components, the present reexport control regulations require that a foreign manufacturer get a reexport license if the U.S.-made content of a foreign-made system exceeds 25 percent of the total content (dollar value), for exports to CoCom countries and specified Third World countries. For proscribed country destinations, the limit on U.S.-made parts and components is 10 percent and $10,000.[28]

This means that if an aircraft built by a company in a CoCom member country includes enough U.S.-made composite parts to fall under the U.S. export control regulations, this company must apply to the United States for a reexport license, as well as to the country of manufacture for an export control license for the entire aircraft. Canada has a similar restriction in that it requires a reexport license for systems containing greater than 80 percent U.S.-made (not Canadian-made) parts and components. These reexport control regulations similarly affect the computer chip and avionics industries.

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[27] Conference on export controls sponsored by the U.S. Department of Commerce for the United States Advanced Ceramics Association, Feb. 24, 1987.

[28] Iain Baird, Department of Commerce, personal communication, Jan. 4, 1988.

For U.S. products that are to be reexported on their own, rather than as part of a system, a reexport license must be obtained for quantities above a certain dollar value. This dollar value is the same as the limit for export from the United States, as given in the U.S. Commodity Control List.

For some products, e.g., ceramics, this threshold dollar value is zero. This low a threshold is chosen to enable control of export of inexpensive items that are critical for weapons systems, e.g., ceramic rocket nose cones; however, advanced ceramic products of greater commercial use are also under this reexport restraint. This suggests that export or reexport control of materials per se may be less efficacious than a more product-specific form of control.

Industry Representation

One mechanism for ensuring that commercial concerns are taken into account in U.S. export control policy is to have representation by nondefense-related industry in policy planning of export controls. Review of the CoCom list is carried out primarily by defense contracting industry personnel, and defense and national security-oriented government representatives. There is no trade-oriented representation on the board that reviews CoCom lists. Of particular concern in this assessment is the lack of channels open for helpful input from the advanced materials industries in export policy controls.

In response to the written requests from a substantial segment of the advanced materials industries, the Department of Commerce formed a Materials Technical Advisory Committee (TAC) in April 1986 to advise and assist in policy discussions stemming from the Export Administration Amendments Act (Public Law 99-64) of 1985.[29] The TAC will provide advice to the Department of Commerce on such issues as technical specifications, worldwide availability, licensing procedures, and unilateral or multilateral export controls.

This materials TAC was formed with the intent of ensuring a more broad-based industry participation in the Commodity Control List review process. To be successful, the committee must bring together members with technical expertise in all of the relevant materials technologies, including those with a trade-oriented viewpoint, and give them a meaningful role in the policy review process. As of this writing, the committee had received many applications for membership.[30]

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[29] Charter of the Department of Commerce Materials Technical Advisory Committee, April 1986.

[30] Jeff Tripp, U.S. Department of Commerce, personal communication, Sept. 21, 1987.

INFORMATION CONTROLS

Perhaps even more than materials themselves, information about how to process them into high-performance structures is considered critical to the national defense. However, excessive controls on the disseminiation of such information can also impede timely development of these technologies in the United States. This information, called "technology" or "technical data" within the system of export controls, can consist of software, patent applications, technical specifications, blueprints, operating manuals, or even technical advice.

To impede the flow of such information to proscribed country destinations, various restrictions, including export license requirements, are imposed by the Federal Government. An individual validated license (IVL) is required by the Department of Commerce for each advanced materials information transaction with a foreign national. Individual validated licenses for up to a 2-year period can be issued for related information transfers to the same company.

The above descriptions of export-controlled information are very broad. One guideline used by the Department of Commerce is to regard export-restricted technical data as any information relating to dual-use or military technologies that could be considered proprietary.[31] However, it is not always obvious what information falls in this category.

It is also difficult to determine what organizations are to be considered foreign. Since the advanced materials industries are increasingly global in scope, and there is an intermingling of U.S. and foreign advanced materials business interests (see ch. 9), the concept of corporate nationality is becoming less and less meaningful. The Department of Commerce currently intends to publish a guideline for determining what constitutes an export of information to a foreign national.[32]

The primary mechanism for information control by the Federal Government has long been the classification system, as reaffirmed in the President's National Security Decision Directive 189 of 1985. Currently, information on advanced materials can also be controlled by ITAR restrictions; EAR restrictions; the Defense Authorization Act of 1984 (Public Law 98-94), which permits restriction of sensitive information (i.e., information on any technology with military or space applications); and government contract restrictions. The many overlapping mechanisms for information control (see table 11-4) can be confusing.

In addition to these mechanisms, there are a host of internal DoD directives, instructions, and guidelines for controlling dissemination of information (table 11-5). The personnel obliged to apply these directives are those within the defense agencies, defense contractors, and the Office of the Secretary of Defense (OSD). These directives and instructions are developed for national security reasons for the control of classified and unclassified information in the context of communications with foreign governments, foreign representatives, and international organizations.

There is a tradeoff inherent in any system of information control between simplicity and flexibility. The present system of many control mechanisms allows flexibility in targeting distribution of information to different audiences. However, having many mechanisms has seemed arbitrary to the private sector and can have a chilling effect on legitimate exchanges of information. A

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[31] Jim Seevaratnam, conference on export controls sponsored by the U.S. Department of Commerce for the United States Advanced Ceramics Association, Feb. 24, 1987.

[32] Ibid.

Table 11-4.—Mechanisms for Controlling Information on Advanced Materials

Mechanism	Agency	Controls	How to access/transfer
International Traffic in Arms Regulations (ITAR) Export Controls	Department of State Office of Munitions Controls	Information on defense articles, services, and related technical data	Apply for an export license
Export Administration Regulations (EAR) Export Controls	Department of Commerce Export Administration Office	Information on "dual-use" technologies	Apply for an export license
Defense Authorization Act of 1984 (10 U.S.C. 130)	Undersecretary of Defense for Acquisition within the Department of Defense	"Sensitive" information with military or space applications—blocks requests under the Freedom of Information Act (Public Law 93-502)	Not to be exported; Canadian, U.S. resident aliens and U.S. access granted through certification form DD 2345, "Militarily Critical Technical Data Agreement"
Classification	Department of Commerce Information Security Oversight Office	Classified information of any nature	Security procedures including clearance and a need to know
Contract Clauses	Federal Acquisition Regulations Council	Any work done for that contract	Distribution can be cleared through the contracting agency

SOURCE: Frank Sobieszczyk, U.S. Department of Defense, personal communication, Nov. 10, 1987.

Table 11-5.—Department of Defense Directives and Instructions for Information Control

Directives:	
5230.27	Presentation of DoD-Related Scientific and Technical Papers at Meetings (Oct. 6, 1987)
5230.25	Withholding of Unclassified Technical Data from Public Disclosure
5230.24	Markings on Technical Documents (Mar. 6, 1987)
Instructions:	
5230.17	Procedures for Disclosure of Military Information to Foreign Governments and International Organizations
5230.20	Control of Foreign Representatives

NOTE: For additional directives and instructions that can be used to control information relating to advanced materials, see table 11-4.

SOURCE: Frank Sobieszczyk, U.S. Department of Defense, personal communication, Nov. 10, 1987.

simpler system, e.g., one involving greater reliance on classification, would be more easily comprehended and complied with by the private sector, but such a system would reduce the ability to control the distribution of information in a flexible manner.

The current information controls can have significant effects on joint ventures, licensing agreements, and customer relations between U.S. and foreign companies. License applications for advanced materials information transfer must be filed to enter into negotiations, during the negotiation process, and after the agreement is made. Significant license application processing delays can discourage the formation of these joint ventures by undermining the faith of a potential foreign partner in the U.S. firm.

Such joint venture and licensing agreements are important to U.S. advanced materials firms. Because the role of the end-user is so significant to investment in advanced materials, materials supplier companies often enter into joint ventures or licensing agreements with end-users to develop a particular technology. Currently, end-user companies willing to explore the commercial possibilities of advanced materials are more easily found in foreign countries. Consequently, some U.S. companies assert that to develop certain materials technologies at all, they must be able to conduct joint venture or licensing arrangements with foreign-owned companies.

Closed Conferences*

In 1982, there was a disruption of a Society of Photo-Optical Instrumentation Engineers (SPIE) conference when, 2 weeks before the conference, DoD informed the society that 20 percent of the 219 papers scheduled, including papers with sponsors other than DoD, could not be presented, even in a closed session.[33] [34] Since then, there have been fears on the part of professional societies that DoD restrictions on presentations at conferences (particularly restrictions imposed at the last minute) will have an adverse effect on both the organization and the conference.

DoD currently imposes certain limits on technical conferences to prevent the export of technology with national security implications, while still permitting its distribution to interested U.S. citizens. In recent years, some professional engineering societies have closed conferences or parts of conferences on their own initiative for fear of last-minute removal of key papers sponsored by DoD. The most notable examples in advanced materials have been conferences on PMCs.

At present, most closed conferences only have one or two closed sessions and foreign nationals may attend the other sessions.[35] In other cases, however, only the exhibit area of a conference is open to foreign nationals, and the advanced technology meetings are closed. DoD maintains that the use of closed sessions at open conferences permits the dissemination of DoD-sponsored research that might otherwise be withheld.[36] Critics note, however, that even the closed sessions are frequently limited in technical content.

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*Closed conference sessions are those from which foreign nationals are excluded; however, see footnote 35.

[33] "Incident over SPIE Papers Muddies Scientific Secrecy Issue," *Physics Today*, June 1985, pp. 55-57.

[34] Eric J. Lerner, "DOD Information Curbs Spread Fear and Confusion," *Aerospace America*, Mar. 1985, pp. 76-80.

[35] Exceptions are foreign nationals from countries whose defense ministries have science and technology agreements with DoD. Foreign nationals from these countries may obtain permission to attend closed sessions. For instance, for advanced composites, these countries are: Canada, the United Kingdom, New Zealand, and Australia.

[36] The procedures for presenting information at a conference with foreign national attendees are the same as those for transmitting a document to a foreign national.

Such restrictions on conference attendence also cause ill-will among foreign researchers and are in any case not a reliable means of preventing information transfer, since a determined individual can readily obtain conference proceedings or admittance to closed sessions. Furthermore, they may be self-defeating from a national point of view in areas where foreign companies and researchers have developed superior technology.

Department of Defense-Generated Databases

There is a wide variety of technical information on advanced materials generated by the military. One major source of this information is the Defense Technical Information Center (DTIC). Participants at an OTA workshop cited DTIC as an underused source of advanced materials technical information and a more complete and up-to-date source than its civilian counterpart, the National Technical Information Service (NTIS).[37]

DTIC maintains two major bibliographic databases, offering information on completed projects that have been sponsored by DoD and the armed services, and on projects that are in progress.[38] In addition, there is a database of military contractors' industrial R&D.[39] The characteristics of the three main databases and distribution listings that allow access to these databases are given in table 11-6. Anyone wishing access to these databases must be a registered user; that is, be endorsed by a DoD agency. To be endorsed, one must be a past, current, or potential government contractor, or a member of a government agency.[40]

All three databases contain some classified or proprietary information. A substantial amount of information contained in DTIC is neither proprietary nor classified but is still limited, meaning that it is only available to registered users. Limited information may consist of software documentation, technologies listed in the MCTL (including all advanced structural materials), technologies falling under other types of export control, information furnished by foreign governments, or administrative information.[41]

Slightly less than 50 percent of the database on completed DoD-sponsored projects is cleared for public release and is available to NTIS. This information is thereby available to anyone, whether

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[37] "Industrial Investment in Advanced Materials," Office of Technology Assessment workshop, Dec. 15-16, 1987.

[38] William Thompson, Defense Technical Information Center, personal communication, Mar. 26, 1987.

[39] Ibid.

[40] Charles Gould, Defense Technical Information Center, personal communication, Mar. 26, 1987.

[41] Department of Defense Directive 5230.24, Distribution Statements for Use on Technical Documents, Mar. 18, 1987.

Table 11-6.—Defense Technical Information Center Databases

Database	Type of information	Proprietary? Classified?	Goes to NTIS?
Bibliographic	Published reports of completed government-sponsored R&D	Not proprietary; some classified	50% does, all basic research identified as being unclassified and unlimited
Work Unit Information System	Government-sponsored R&D in progress	Not proprietary; some classified	None; distribution only to DTIC-cleared users
IR&D	Company-sponsored research of interest to government	All proprietary and some classified	None; only open to DoD and other agencies, *not available to contractors*
Department of Defense R&D Program Plannning (not in place yet)	Descriptive summaries	Some classified	Possibly Congressional distribution; not open to public
Proposed Database (untitled)	Database of all DoD agency databases	Both proprietary and classified	Distribution unknown

NOTE: Each document in these databases is cleared for distribution to one of the categories of users below:
a. U.S. Government only
b. U.S. Department of Defense only
c. U.S. Government agencies and their contractors
d. U.S. Department of Defense and its contractors
e. Domestic public/U.S. citizens.

SOURCE: William Thompson, Defense Technical Information Center, personal communication, Mar. 26, 1987.

a U.S. or foreign citizen.[42] Information on DoD-sponsored projects in progress is available only to DTIC users and not to NTIS. Only a small percentage of applied R&D in DTIC goes to NTIS.[43]

A DoD directive requires the individual armed services to contribute information to DTIC databases. At present their compliance with this directive represents only about 60 percent of known reports.[44] The armed services and other DoD agencies (e.g., the Defense Advanced Research Projects Agency, DARPA) maintain their own separate technical databases. DTIC is now working to develop a database of all available DoD agency technology databases.

Access to DTIC databases by firms not under contract to the government is quite difficult because DTIC is not authorized to extend information to other than contractors and potential contractors. A potential subcontractor company can be helped to enter the defense community by working with an established primary contractor. Each service also has a potential contractor program to help companies access the DTIC.

DTIC contains a significant amount of information on advanced materials that is neither proprietary nor classified (and would contain more if the directive requiring submission of DoD-sponsored reports were fully complied with). This information would be of interest to commercial, market-oriented firms, but is unavailable to them. By permitting greater access to the technical information in DTIC by commercial firms, subject to necessary restrictions on proprietary or classified information, DoD could help to make more efficient use of its R&D investments, and to promote the timely transfer of technology to the commercial sector.

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[42] Charles Gould, op. cit., Mar. 26, 1987.

[43] William Thompson, Defense Technical Information Center, personal communication, Mar. 26, 1987.

[44] Ibid.

TECHNOLOGY TRANSFER FROM THE MILITARY

There has long been a debate over the extent to which technologies developed to fulfill DoD mission requirements can be spun off and used in commercial applications.[45] In general, technology transfer occurs most readily at the level of basic research.[46] As the research becomes more system-specific, or in the case of military R&D, more mission-specific, transfer is more difficult.[47] Effective technology transfer may also occur when the military and commercial applications are similar and the same companies are involved.

The military investment in advanced materials has accelerated the development of the advanced materials industries, but its benefits for commercial use of the materials remain in doubt. On the positive side, the fact that these higher performance materials have been developed to the extent that they have is largely due to the experience gained by using these materials in weapons systems. DoD funds a great deal of basic research of broad general interest. In addition, there can be significant overlap between the materials requirements of certain military and commercial systems. For instance, much of the PMC technology used in civil aircraft has been derived from military PMC applications. As experience is gained in the production of these materials for military purposes, manufacturing costs can decrease, thereby facilitating technology transfer to commercial endeavors.

DoD also supports research in materials processing technology; for instance, DoD's Manufacturing Technologies (ManTech) program (see table 11-7) has provided funds for composite materials processing research such as the B-1B wing project sponsored by the Air Force Materials Laboratory.[48] This project, conducted by Rockwell, Avco/Textron, and Hercules Aerospace, uses automated tape laying, filament winding, and other innovative techniques to construct wing

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[45] J. David Roessner, "Technology Policy in the United States: Structures and Limitations," *Technovation*, vol. 5,1987, p. 240.

[46] Ibid.

[47] Ibid.

[48] "Rockwell Team Demonstrates Automatic Construction of Large Composite Wings," *Aviation Week & Space Technology*, June 15, 1987, pp. 333-338.

Table 11-7.—Manufacturing Technology (ManTech) Program Funding Levels for Advanced Materials-Related Projects (millions of dollars)

Category	Fiscal year 1986	Fiscal year 1987	Fiscal year 1988
Air Force[a]	7.5	8.6	13.4
Navy[b]	1.6	1.1	3.0
Army[c]	0.5	0.9	1.4
Total	9.6	10.6	17.8
Total ManTech[d] funding	205	124	165

NOTES: About 3 percent of ManTech funding goes to the Defense Logistics Agency. While DARPA and SDIO sponsor signficant materials processing R&D, they are not formally under the ManTech Program.

SOURCES:
[a]Thomas Fitzgerald, U.S. Department of Defense, Air Force.
[b]Chris Current, U.S. Department of Defense, Navy.
[c]Ken Rice, Army Materials Technology Laboratory.
[d]Lloyd Lehn, U.S. Department of Defense, Office of the Secretary of Defense.

skins, box spars, ribs, and stiffeners. Total funding for this program is $7.5 million since September 1983.[49] Research such as this, funded by the military, can lead to more cost-effective production methods.

However, in many cases, there are few technical synergisms between military uses and potential commercial applications. The military applications of advanced materials require high performance, and cost is typically a secondary consideration. The difference in acceptable material and manufacturing costs between military and commercial structures can be orders of magnitude, and thus military production methods and materials may not be directly transferable.

The difference in acceptable costs is illustrated by the fact that the graphite fibers used in military PMC structures cost at least $25 per pound (and may cost over $1,000 per pound), whereas the E-glass fibers used in automobiles cost $0.80 per pound (see ch. 8). Large cost differences also exist between aerospace epoxy matrix materials and automotive poly- and vinyl-ester matrices.[50]

Similarly, the process of hand lay-up of PMCs, used in the production of military aircraft components, would be too expensive and time-consuming to apply to automotive use. Hand lay-up produces pounds per hour of material, whereas, to be economically feasible in automobile manufacturing, pounds of material per second must be produced, using such processes as resin transfer molding.

It is difficult to transfer technology when the military and commercial systems requirements are different. The recently proposed National Aerospace Plane (NASP) provides an illustration of this. As a commercial aircraft, the NASP is envisioned as passenger carrier that would be able to fly halfway around the globe in 2 hours, opening up large potential markets of travel between the United States and the Far East. Nicknamed the "Orient Express" by President Reagan, this commercial aircraft would have to be able to attain speeds of about Mach 5 and be capable of cruising at altitudes of 30 to 40 kilometers.[51]

The military is also interested in the NASP as a platform for launching small payloads into space. Such a launch vehicle would have the advantage of being reuseable and having conventional take-off and landing capability. However, military requirements for this type of plane are much higher than are necessary for a commercial version. The NASP is under consideration as an SDI launcher because it would offer much-needed lower launch costs. In contrast to the Mach 5 capability of the commercial version, the military version would have to achieve Mach 25 to attain Earth orbit.[52] This could require different propulsion systems (turbo ramjet vs. scramjet engines) as well as far more heat-resistant materials than for the commercial plane. To meet the extreme performance (high temperature) demands for the NASP, advanced materials technologies will play a large part. For a cruising speed of Mach 3, average temperatures can reach 630° F (332° C) at the leading edges of wings.[53] Titanium alloy aircraft skins start to weaken at 1,000° F (538° C), which occurs after a few seconds at Mach 5.[54] At the higher Mach numbers, wing leading edge temperatures as high as 4,000° F (2,205° C) could be reached. Ceramic matrix composites or carbon/carbon composites would be required for the hottest structures, and metal matrix composites could be used in the cooler structures.

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[49] Ibid.

[50] P. Beardmore, C.F. Johnson, and G.G. Strosberg, "Impact of New Structural Materials Technology—Case Study: Composite Automobile Frame," contractor report prepared for the Office of Technology Assessment, Mar. 1987.

[51] Jerry Grey, "The Aerospace Plane: The Timing Is Right," *Issues in Science and Technology*, Spring 1987, p. 18.

[52] James F. Loomis, Battelle Memorial Institute, *Toward a Hypersonic Commercial Transport*, talk given at the Office of Technology Assessment, Washington, DC, Jan. 13, 1988.

[53] "High Speed Commercial Flight: The Coming Era," James P. Loomis, ed., (Columbus, OH, Batelle Press, 1987, p. 193.

[54] T.A. Heppenheimer, "Launching the Aerospace Plane," *High Technology*, July 1986, p. 47.

PROCUREMENT ISSUES

Military markets for advanced materials are unique in that the Federal Government is the principal customer. Because of this, participation of U.S. advanced materials companies is dependent on DoD policies and regulations, rather than on conventional economic criteria. The overriding DoD policy objectives are to secure reliable domestic sources of advanced materials and the widest selection of materials technologies at the lowest possible cost. DoD procurement policies that strongly influence the cost and availability of materials technologies include materials qualification requirements and domestic sourcing requirements. DoD procurement issues not covered in this assessment include military specifications and DoD auditing.[55]

Materials Qualification Databases

Before a material can be used in a military system, it must be "qualified" for use. As indicated below, the time and cost involved in testing a material for qualification are substantial. While it is desirable to have a rigorous screening procedure to assure performance and reliability, inefficiencies in the present system of qualification can limit the number of materials available and can add to their cost.

In the aerospace industry, materials databases are continually being developed for the purpose of qualifying new materials or new combinations of materials. Aerospace prime contractors conduct extensive testing on potentially useful materials, to avoid any possibility of liability due to structural failure. Each prime contractor maintains proprietary databases as well as expensive in-house testing facilities dedicated to its preferred methods of testing. Taken together, though, these databases carry redundant information, and their development is costly to the military, materials suppliers, and prime contractors. Also, they require a great deal of time to generate.

It costs as much as $10 million each for databases on individual new materials.[56] This process can involve up to 3,000 individual tests by the prime contractor and a similar amount by the material supplier.[57] Most of this $10 million for a database comes from the Federal Government.[58] This is the cost of a first database development; retesting for these databases occurs at a cost of roughly $1.5 million per additional set of tests.[59]

Under the present system, if six contractors intend to use a given material for an application, the material is qualified six times, each by a separate set of tests. If the same material is used by the same contractor but in a different application, it must be qualified again.

The cost of qualification varies depending on how much of the material is new (see table 11-8 for types of material and associated costs). The time taken in qualifying a new material can be more important to a company than the direct cost; it can take up to 2 years to qualify a new material.[60] Overall, the time and expense in-

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[55] For a discussion of DoD procurement issues, see U.S. Congress, Office of Technology Assessment special report, "The Defense Technology Base: Introduction and Overview, OTA-ISC-374 (Washington, DC, U.S. Government Printing Office, March 1988)

[56] Michael Dubberly, Naval Air Command, Suppliers of Advanced Composite Materials Association, Annual Meeting and Industry Conference, May 5-8, 1987.

[57] Richard Ostlund, Boeing Vertol Company, Suppliers of Advanced Composite Materials Association, Annual Meeting and Industry Conference, May 5-8, 1987.

[58] Independent Research and Development (IR&D) funding is used for much of the development of these databases. IR&D funds are charged to the Federal Government as overhead by contracting companies, for the purpose of internal research related to a given contract. Generally these funds are some 2 to 6 percent of the contract and their use is determined by the company, with the government acting as an auditor. Government contractors consider IR&D money to be private in nature; there is a significant amount of debate in the Federal Government as to whether this overhead charge should be considered public or private.

[59] Dubberly, op. cit.

[60] Ibid.

Table 11-8.—Qualification Costs of New Materials

Vendor/material	Cost	Time to qualify
Same material system; new vendor	$300,000	6 months
Equivalent resin; same fiber	$1.5 million	one year
Same resin; new fiber	$6-8 million	18 months
New resin; new fiber	$10 million	2 years

NOTE: Median values given. Cost depends on: how much material will be used, in which parts of the plane, service environment, and specifications. In general, using the same material in a different application, the material must be requalified.

SOURCE: Michael Dubberly, Naval Air Command, Suppliers of Advanced Composite Materials Association, Annual Meeting and Industry Conference, May 5-8, 1987, Washington, DC.

volved in qualifying a new material can add up to a significant deterrent to testing new, possibly better materials in situations where there is already an available qualified material.

No fully satisfactory solution to the problem of overtesting has been suggested. However, possibilities for reducing the number and cost of materials databases have been proposed. DoD could promote the introduction of standardized testing. There are several groups that are each planning to develop limited sets of testing and materials standards. These are described in ch. 5, and include: the Aircraft Industries Association Composite Materials Characterization, Inc.; the Suppliers of Advanced Composite Materials Association; DoD's Standardization Program, (Composites Technology Program Area), directed by the Army for use by the Military Handbook 17 (MIL-17); and the Amercian Society for the Testing of Materials (ASTM). DoD could also promote greater sharing of data among prime contractors, and between prime contractors and materials suppliers. However, this would meet with considerable resistance from prime contractors who see these databases as proprietary in nature. Solutions to the overtesting problem are likely to involve some combination of the above.

Domestic Supply of Advanced Materials

There are several methods the Federal Government can use to ensure sufficient domestic supply of strategic and critical materials and to promote the well-being of the domestic industrial base via Federal Government purchases.[61] It is possible to establish domestic supplies of various products via the Defense Production Act of 1950 (50 USC 2166a).[62] Title III of that act authorizes purchase guarantees and loans to ensure domestic production capacity of certain materials (for instance, purchase guarantees for stockpiling of pitch-based fibers). It is also possible to establish domestic supplies of materials via the amended Defense Production Act of 1984 (Public Law 98-265)[63], and the annual Defense Authorizations or Appropriations Acts.[64]

Present U.S. markets for composites are dominated by military needs. Accordingly, DoD and the Congress have taken steps to ensure an adequate domestic supply and production capacity of certain composite constituents. Of particular importance to the advanced PMC community is the current requirement for assuring domestic sources for PAN (polyacrylonitrile) carbon fiber precursor, which Congress mandated in the Department of Defense Appropriations Act of 1987. PAN precursor is drawn into fibers and then heated to 1,600° F to form the carbon fiber.

Carbon fiber derived from PAN precursor is the single most important fiber used in advanced composites for aircraft and space applications. As of this writing, 100 percent of PAN precursor for fibers qualified for military use is imported from Japan and the United Kingdom. The United States currently has domestic production facilities for all phases of PMCs, from fibers and resins to finished components, except for the production of PAN fiber precursor. Amoco Chemical Co. has production facilities in the United States for PAN precursor but prior to this directive, the company was not a qualified supplier. Although Amoco is currently working toward qualifying as a domestic military supplier, DoD still requires a second domestic source, opening up opportunities for other companies as well.

The Congressional mandate follows an initiative by DoD to devise a plan (which has been under consideration since 1985[65]) for the development of a domestic base of PAN precursor production. Congress has set requirements for 15 percent of all PAN used in military systems to be domestically sourced by 1989; 20 percent by 1990; 25 percent by 1991 and 50 percent by 1992.[66] Congress also endorsed the planning approach of DoD, which is to designate several high technology weapons programs to use 100 percent domestically-sourced PAN fiber. As of March 1988, no guideline has been developed by DoD for implementing this procurement plan.

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[61] Marvin Goldstein, Department of Defense, personal communication, March 30, 1987.

[62] Ibid.

[63] DoD identifies the specific projects after Congress authorizes the funds.

[64] Ibid.

The lack of a detailed plan has caused confusion among fiber vendors. Because material suppliers generally sell to particular prime contractors for specific weapons systems, it is important to industry to know the systems that will require domestic PAN fiber. Qualification of new fibers is also system-specific and must occur as the design of the system occurs. This means that a new domestic PAN precursor plant must be built in time to begin the qualification process while the weapon system design is still flexible. With no guarantees as to which systems would require domestic PAN fibers, individual companies do not know whether undertaking such a sizable investment would pay off.

Another concern on the part of potential U.S. precursor suppliers is that once production facilities are established in the United States, the Federal Government will not want to pay higher costs incurred initially for domestic PAN fiber precursor. A plant to produce PAN precursor costs as much to build as a plant to produce the carbon fiber from the precursor.[67] There is general agreement in industry that domestic fiber will cost more than imported fiber, at least in the beginning. Industry representatives are concerned that commitment to domestic sources will not hold if less expensive foreign-made precursor is available.

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[65] Because of the importance of PAN-based carbon fiber PMCs to military systems, the Under Secretary of Defense for Research and Engineering issued a statement in 1985 expressing concern that there be some domestic source of production of PAN fiber precursor, and a policy directive was subsequently developed for achieving this.

[66] U.S. Congressional Record, No. 205, Part III, (Washington, DC, U.S. Government Printing Office, Dec. 21, 1987), pp. H12546-547.

[67] William Bennett, Amoco Performance Products, Inc., personal communication, Apr. 13, 1987.

OFFSETS

Offsets involve an agreement between a U.S. high technology systems manufacturer and a foreign buyer in which production technology is transferred to the buyer to promote the sale. Offsets are commonly used by U.S. aircraft manufacturers to promote sales of aircraft abroad. Historical examples of offsets include transfer of aluminum forging or PMC technologies to such nations as Canada, Sweden, France, Italy, Spain, the Netherlands, and Japan to encourage them to buy military aircraft such as the F-16 and the F-18, or commercial aircraft such as the Boeing 757, the 767, and the McDonnell-Douglas MD-80.[68] [69]

Offsets are useful in promoting U.S. foreign policy interests. They also help achieve sales for U.S. aircraft manufacturers, who are not competing directly with the buyer. However, offsets can be harmful to the competitive position of materials suppliers, since suppliers may be compelled to transfer proprietary technology to potential competitors abroad.

In accordance with the Defense Production Act Amendments of 1984 (Public Law 98-265), Congress requires an annual report on offsets from the Office of Management and Budget. However, the situation is not currently receiving much attention. This is because offsets are only a small part of a larger picture of aircraft sales, which includes foreign policy goals such as rights to maintain air bases, coastal access or protection, or other policies not directly related to the sale of aircraft. Foreign nations wishing to purchase costly weapons systems require offsets to increase their domestic technology capabilities. Offsets are not merely a practice concerning a foreign nation or buyer and a U.S. vendor as part of an aircraft trade negotiation. They are part of the package of foreign policy actions that the United States undertakes as a military and economic superpower.

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[68] James N. Burns, Hercules, Inc., personal communication, Apr. 20, 1987.

[69] Greg Barthold, Aluminum Company of America, personal communication, Mar. 5, 1987.

Offsets are a primary mechanism by which proprietary materials technology is transferred abroad. Advanced composite technology has already been transferred via offsets by airframe manufacturers to Spain, Italy, Sweden, and Japan on sales of commercial aircraft. Sales of military aircraft have included offsets of advanced aluminum processing technologies to Japan and France. Airframe manufacturers consent to offsets because they are required by foreign countries in requests for bids. Materials suppliers tolerate this loss of proprietary technology because to do so allows them to compete in a situation where all suppliers must offer offsets.

Another practice related to offsets, and detrimental to the U.S. advanced material supplier, is that of coproduction. A foreign country purchasing aircraft may require that parts of the aircraft be produced in that country. This is a situation where a U.S. prime contractor helps to set up a plant in a foreign country that is contracted to supply components or materials processing technology. This is technology that a U.S. advanced materials company could supply.

Offset agreements, as with other types of trade in advanced materials, must receive export licenses to proceed. Export controls exist, however, not for economic protection, but for national security and foreign policy reasons. The trade-offs in offset agreements are not only between national security and economic concerns, but also between national security and foreign policy. The two seemingly contradictory processes of offsets and export controls are focused on different goals (foreign trade, national security, and foreign policy) that are increasingly difficult to pursue concurrently in the highly integrated world marketplace.

There are many forms of offset practices. Although not easily calculated, their impacts on the competitiveness of advanced materials industries are believed to be extensive by many industry experts. A thorough, up-to-date analysis of the costs and benefits of offsets is desirable.

THE BALANCE OF COMMERCIAL AND MILITARY INTERESTS

With the growing dependence of the military on a range of high technologies, including advanced materials, DoD can be expected to take a larger policy role aimed at ensuring a domestic production capacity for key technologies. The large DoD funding for the Sematech Microelectronics Consortium ($100 million for 1988[70]) is one example of this trend; the PAN precursor procurement described above is another. DoD plans for a more comprehensive industrial policy were described at a May 1987 workshop held by the Suppliers of Advanced Composite Materials Association (SACMA).[71] This policy initiative, intended for the preservation of the U.S. industrial base, proposes targeting particular technologies, among them machine tools, bearings, castings, semiconductors and advanced composites, for DoD support. The policy initiative will address such issues as domestic technology erosion, availability of trained scientists and engineers, acquisitions of U.S. firms by foreign firms, contract and regulatory reform, research and development, energy, intellectual property rights, international cooperation, U.S. government-industry-academia collaborations, and better relations between DoD and the business community. Targeting of particular industries is deemed crucial.

If military investment is to benefit commercial materials applications, and vice versa, there must exist a broader policy perspective on materials.

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[70] *IEEE Spectrum*, February, 1988, p. 3.

[71] Robert Costello, Department of Defense, Annual Meeting and Industry Conference, Suppliers of Advanced Composite Materials Association, May 5-8, 1987.

To enhance the long-term competitiveness and health of the advanced materials industries, it will be essential to balance military and commercial interests more effectively. Options for taking better commercial advantage of military investments are discussed in the next chapter.

Chapter 12

Policy Issues and Options

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Chapter 12

Policy Issues and Options

FINDINGS

Given the high risks associated with the commercialization of advanced materials, the Federal role in accelerating this process is likely to continue to be very important. OTA identifies four general Federal policy objectives that could improve the climate for commercialization of advanced materials in the United States. Options for pursuing these objectives range from those with a broad scope, affecting many technologies, to those specifically affecting advanced materials.

Objective 1:

Encourage long-term capital investment in advanced materials by potential end users.

Greater advanced materials investments by potential end users would help to generate more commercial market pull on advanced materials in the United States. The climate for such investments can be improved by several policy options aimed at making patient capital available, including providing tax incentives for long-term capital investments, reducing the cost of capital by encouraging greater national savings, and comprehensive tort law reform aimed at making product liability costs proportional to proven negligence.

Objective 2:

Facilitate government/university/industry collaboration in R&D for low-cost materials fabrication.

The high cost of advanced materials development and the small near-term markets are forcing companies to seek collaborative R&D arrangements to spread risks and raise the large amounts of capital required. Three major reservoirs of materials expertise are available to U.S. companies: universities, Federal laboratories, and small high-technology firms. At present, industry considers the scale-up costs too high and the payoffs too uncertain to justify commercialization of research results from current industry/university and industry/Federal laboratory collaborations. The government could encourage the commercialization step by establishing collaborative centers in which government and industry would share the costs of downstream materials fabrication technology development. An alternative would be to provide incentives for large companies to work with those small, high-technology firms that have advanced materials fabrication expertise, but lack the capital to explore its commercial potential.

Objective 3:

Facilitate more effective commercial exploitation of military R&D investments where possible.

The large U.S. military expenditures on advanced materials technology development represent a potential boost to the commercial competitiveness of U.S. firms. However, national security restrictions imposed on militarily important materials and processes can also inhibit commercial development. Ultimately, both national security and a competitive commercial manufacturing base depend on a strong domestic advanced materials capability. Therefore, a major objective of U.S. policy should be to balance these conflicting interests, and, where possible, to make it easier for commercial firms to exploit this resource. Among the options which could be considered are a greater advisory role for commercial materials companies in reviewing export control policy; greater support for military programs aimed at developing low-cost materials and fabrication processes; and clarification of military domestic sourcing policies for advanced materials.

Objective 4:

Build a strong advanced materials technology infrastructure.

A broad range of technical data and an adequate number of trained personnel must be available to exploit materials technology developments in a timely fashion, whether they originate in the United States or abroad. The Federal Government could gather and disseminate information on ongoing R&D projects, business statistics, and technical developments abroad. It could also provide increased support for efforts aimed at establishing standard test methods for advanced materials, and for the development of databases containing relevant design and processing information. Increased funding could also be provided for university programs in advanced ceramics and composites, and for retraining programs for engineers who are not familiar with the new materials.

Congress and the Administration have adopted conflicting views of advanced materials. According to the congressional view, national goals and priorities should be established for advanced materials R&D above the agency level, and agency spending on materials programs should be made consistent with them. This view is expressed in the National Critical Materials Act of 1984, in which Congress established the National Critical Materials Council (NCMC) in the Executive Office of the President. The NCMC is charged with the responsibility of working with the principal funding agencies and the Office of Management and Budget to define national goals and priorities for materials R&D, and to coordinate the various agency efforts in developing a national program plan for advanced materials.

In the Administration's view, priorities for advanced materials R&D cannot be separated from the functional requirements of the structures in which they are used. Because different agencies have different requirements for materials, determination of R&D priorities is best made at the agency level. According to this view, the information exchanged through various existing interagency materials committees is adequate to avoid excessive duplication and waste. The NCMC is considered redundant with these committees.

OTA finds that it is more difficult to define national policy goals for advanced materials than for more traditional critical materials. To succeed in its task, the NCMC will need to establish a more precise definition of the goals that would motivate a national materials policy, as well as to develop high-level Administration commitment to the concept of such a policy. At present, Congress and the Reagan Administration remain far apart in their views of the appropriate scope of a national materials program plan, and of the role of the NCMC. Pending the resolution of these differences, there are three further functions that the NCMC could perform:

- a point of contact for monitoring industry concerns and recommendations regarding joint industry-government initiatives;
- gathering information on domestic and foreign materials R&D efforts and disseminating it to industry; and
- a broker for resolving conflicts between military and commercial agency goals for advanced materials.

INTRODUCTION

Advanced materials technologies clearly represent great potential opportunities for the U.S. economy. Today, materials account for between 30 and 50 percent of the costs of most manufactured products. In the 1990s and beyond, introduction of new materials that can reduce overall production costs and improve performance will be an important factor determining the competitiveness of U.S. manufactured products such as aircraft, automobiles, and industrial equipment.

But will the United States be able to capitalize on these opportunities? In spite of the fact that the United States invests more Federal money in materials R&D than any of its foreign competitors, there is serious doubt as to whether U.S. industry will aggressively transfer this R&D into commercial products.

Perhaps the central finding of this assessment is that potential commercial end users of advanced materials, whose investment decisions are determined by expected profits, do not believe that use of these materials will be profitable within their planning horizon of 5 years. Thus, there is virtually no market pull on these technologies in the United States. While U.S. commercial end users have placed themselves in a relatively passive, or reactive role with respect to use of advanced materials, their competitors, notably the Japanese, have adopted a more aggressive, "technology push" strategy. This strategy involves incorporating advanced materials into existing products to gain manufacturing experience for the future. In contrast to the United States, where industry and government investments in advanced ceramics and composites research are roughly comparable, in Japan such research is overwhelmingly funded by private industry.

On the whole, a strong case can be made that the profit expectations of U.S. advanced materials end users are accurate, within the 5-year time horizon. In most cases, it will take longer than 5 years to develop solutions to the remaining technical and economic problems. Although precise production cost data are not available, it is likely that Japanese structural ceramic components are not produced at a profit; rather, the Japanese firms gain the manufacturing experience necessary to position themselves favorably for future opportunities. Early indications are that these efforts have been successful. While the U.S. Department of Energy has provided massive funding to a consortium of companies to develop ceramic gas turbine engine prototypes for automobiles since the late 1970s, the most highly stressed component of these engines, the ceramic turbine rotor, is currently made in Japan.

This Japanese technology push strategy is not without risks. In addition to reducing profits in the near term, it may also lead to premature commitment to obsolescent technology. Historically, Japan has concentrated on making incremental improvements in the properties of monolithic structural ceramics, whereas the United States has given greater emphasis to developing tougher (and more expensive) ceramic matrix composites (CMCs). Japan now appears to be shifting more resources toward CMCs.[1]

Ultimately, the future competitiveness of U.S. advanced materials industries in worldwide commercial markets will depend on the investment decisions made within the industries themselves. The risks of such investments are high. To develop a manufacturing capability with advanced structural materials requires enormous capital investment, while the payoffs are often 10 to 20 years away. However, most experts contacted by OTA stressed that manufacturing experience over time with advanced materials is essential; U.S. companies cannot expect to step in and produce competitive advanced materials products after the manufacturing problems have been solved by others.

The Federal Government directly affects the development of advanced materials through funding of basic research, technology demonstration programs associated with the missions of Federal agencies, and military/aerospace procurement of advanced materials and structures. State and Federal policies and regulations, such as R&D tax incentives and product liability laws, also indirectly affect the climate for industry investment in long-term, high-risk technologies such as advanced materials.

Of the roughly $167 million invested by the Federal Government in advanced structural ceramics and composites R&D in fiscal year 1987,* about 60 percent was sponsored by the military. This proportion would have been even higher if military funds for testing, evaluation, and classified programs had also been included. Advanced materials are truly enabling technologies for military missions. Without their unique properties, including high strength and stiffness, light weight, and high-temperature capabilities, many of the major military programs under development, such as the Strategic Defense Initiative, the National Aerospace Plane, and various Stealth weapons systems, would not be feasible.

Historically, programs within the Department of Defense (DoD) and, to a lesser extent, the National Aeronautics and Space Administration (NASA), have driven the development of many advanced materials, particularly various kinds of composites. The high cost of advanced materials for military applications is justified by the high performance they deliver. As long as this emphasis continues, the military will remain one of the largest and fastest growing markets for new materials.

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[1] Dick J. Wilkins, Director, Center for Composites Research, University of Delaware, personal communication, November 1987.

*This total encompasses R&D involving: monolithic ceramics; ceramic, polymer, and metal matrix composites; and carbon/carbon composites.

The commercial benefits of military materials investments remain controversial. Military applications often help to boost a new technology up the learning curve, and new materials are made available that otherwise would have gone unexplored. However, because the cost of military materials is typically high and production volumes are low, often neither the materials nor the production methods are appropriate for commercial applications. For national security reasons, the military may also place restrictions on the dissemination of DoD-funded materials R&D, thereby creating an additional barrier to the diffusion of R&D results into the commercial sector.

In military applications, the government is the customer for materials technology and hardware. As such, it has an interest in securing stable, domestic sources of material supply. However, military markets will not be large enough to sustain a viable domestic advanced materials industry in the future. Critics charge that the expanding military role is likely to skew the national advanced materials agenda toward development of more exotic, high-performance materials, such as carbon/carbon composites, and to low-volume, high-cost manufacturing processes that will have at best indirect benefits for commercial applications. These concerns are all the more acute given that the other countries—notably Japan, which has a very small military establishment—are already giving heavy emphasis to commercial uses of advanced materials.

About 40 percent of Federal spending for advanced structural ceramics and composites R&D is nonmilitary in nature, including most of that funded by the Department of Energy (DOE), NASA, the National Science Foundation, the National Bureau of Standards, and the Bureau of Mines. These civilian agencies generally do not act as the procurers of hardware. Rather, they sponsor materials R&D performed by universities, Federal laboratories, and industry contractors. The R&D ranges from basic science to technology demonstration programs, according to the particular agency's mission objectives.

Where appropriate, the civilian agencies encourage industry to commercialize the new technologies. To date, though, these efforts have not been very successful, in large part because industry has lacked the near-term market incentives necessary to justify the costs of adapting these technologies for commercial production. The recent concern about U.S. industrial competitiveness has focused attention on how this federally funded research can be transferred more effectively to the private sector.

If U.S. advanced materials industries are to be competitive in the future, more will be required than early leadership based on military investments. The United States has learned from bitter experience in microelectronics that early technological dominance is no guarantee of long-term competitiveness. Technologies flow rapidly across national borders, and a competitor who comes second to market may enjoy the benefits of the leader's efforts but have lower production costs. One example of the rapid loss of a new materials market is the electronic ceramics industry, which constitutes about 80 percent of the value of all advanced ceramics produced today. In the past 10 years, the United States has largely lost the electronic ceramic components business to Japan, particularly in the important area of integrated circuit substrates and packages.

Why has Japanese industry been able to make such a massive commitment to such a risky technology as structural ceramics? Observers suggest several reasons. In Japan, aggressive movement into promising new technologies is considered less in terms of short-term economic return than as a matter of long-term survival for Japanese industry. This sense of vulnerability and urgency is generally lacking in Western business plans. A second reason is that Japanese industry enjoys a relatively low cost of capital, in large part due to the high national savings rate. A third reason is the capacity of the Japanese system to spread the risks effectively among the many participants in the precompetitive stage of technology development. This is facilitated by the close cooperation among the Japanese Government, financial institutions, and the highly integrated advanced materials companies.

PROJECTIONS BASED ON CONTINUATION OF THE STATUS QUO

Given that the Federal Government plays such an important role in advanced materials development, it is evident that government policy choices will have a significant effect on the competitiveness of U.S. advanced materials industries. Before discussing policy issues and options, though, it is useful to consider scenarios that can be projected based on continuation of current trends.

Because U.S. military markets will expand faster than commercial markets in the near term, the military role in determining the development agenda for advanced materials is likely to broaden. As explained above, military investments in advanced materials could be an asset to U.S. firms; however, they could also tend to skew advanced materials activities in the direction of high-performance, high-cost materials inappropriate for commercial applications.

Meanwhile, the reluctance of U.S. commercial end users to commit to advanced materials suggests that foreign firms will have an advantage in exploiting the growing global markets. Almost certainly, a successful product using an advanced material produced abroad would stimulate a flurry of R&D activity among U.S. companies. However, given the lack of experience in the United States with low-cost, high-volume manufacturing technologies for advanced materials, U.S. companies would be faced with a formidable challenge in trying to catch up.

The high cost of R&D, scale-up, and production of advanced materials, together with the poor near-term commercial prospects, will drive more and more U.S. companies to pool resources and spread risks through a variety of joint ventures, consortia, and research centers. Currently, many such collaborative programs are springing up across the country. These programs will provide an excellent environment for generic research and the training of students. However, they will not necessarily lead to more aggressive commercialization of advanced materials by participating companies (see ch. 10).

Worldwide, advanced materials industries will continue to become more multinational in character through acquisitions, joint ventures, and licensing agreements. Technology will flow rapidly between firms and across national borders. For U.S. companies, critical advances will continue to come from abroad, and the flow of materials technology into the United States will be as important as that flowing out. U.S. efforts to regulate these flows for national security reasons will meet increasing resistance from multinational companies intent on achieving the lowest production costs and free access to markets.

These projections suggest there is reason to doubt that the United States will be a world leader in advanced materials manufacturing in the 1990s and beyond. The full-scale commercialization of these materials is presently blocked because they do not meet the cost and performance requirements of potential end users.

PROPOSED POLICY OBJECTIVES AND OPTIONS

OTA believes there are four general government policy objectives which could help to reduce the barriers to effective commercialization of advanced materials in the United States.

1. Encourage long-term capital investment in advanced materials by potential end users.
2. Facilitate government/university/industry collaboration in R&D for low-cost materials fabrication processes.
3. Facilitate more effective commercial exploitation of military R&D investments where possible.
4. Build a strong advanced materials technology infrastructure.

The following discussion of policy options is framed by these four general objectives. Options range from those with a broad scope, affecting many technologies, to those specifically affecting advanced materials. These options are not mutually exclusive, and most could be implemented without inconsistency.

Following the discussion of policy options is a section on alternative approaches to setting the Federal Government goals and priorities with regard to advanced materials.

Encourage Long-Term Capital Investment by Advanced Materials End Users

Greater investment in advanced materials by potential end users would generate more market pull on these technologies in the United States. The shortfall of long-term investment in advanced materials by potential end-user companies reflects a more widespread shortfall found in many U.S. industries. Such shortfalls have been attributed to a variety of generic barriers to the commercialization of emerging technologies, as summarized in table 12-1. (Many of these barriers were also identified as critical by materials industry representatives contacted by OTA as described in ch. 8.)

Table 12-1.—Commonly Cited Generic Barriers to Commercialization of Emerging Technologies in the United States

- High costs of capital funds in the United States relative to foreign competitors
- Lack of tax incentives for U.S. companies relative to foreign competitors to deploy emerging technologies (including the stability of tax regulations)
- Poor integration of manufacturing, design, and R&D functions
- Inadequate laws, regulations, and enforcement protecting intellectual property rights in the United States or overseas
- Complacency of U.S. manufacturers and dependence on the domestic market
- Restrictive trade policies in foreign markets
- Time-consuming Federal and State regulations on corporate activities intended to protect the public health and safety (e.g., building codes, environmental laws, drug approval regulations, and occupational health regulations)
- Export controls on advanced technologies and high-technology products
- Uncertainty caused by product liability and tort laws
- Anti-trust restrictions against cooperative ventures for marketing or production methods

SOURCE: U.S. Department of Commerce, "The Status of Emerging Technologies: An Economic/Technical Assessment to the Year 2000," report to the Deputy Secretary of Commerce by the Emerging Technologies Committee, 1987.

The climate for long-term industry investment is strongly affected by Federal policies and regulations, including tax policy, intellectual property law, tort law, and environmental regulations. Public debate regarding the relationships between these Federal policies and regulations and U.S. industrial competitiveness has given rise to a voluminous literature. Suggested policy changes include: providing tax incentives for long-term capital investments; reducing taxation on personal savings and corporate retained earnings to make more investment capital available and thus reduce its cost; revising banking law to encourage financial institutions to make patient capital available; and enacting comprehensive tort law reform aimed at making product liability costs proportional to proven negligence.[2]

Such policy changes affect the general climate for innovation, and have been extensively discussed elsewhere.[3] They have implications far beyond advanced materials technologies, and an analysis of their effects is beyond the scope of this assessment. Although it is conceivable that such broad policy instruments could be narrowed to focus on advanced materials technologies specifically, there would appear to be little justification for singling out advanced materials—as opposed to, say, microelectronics, computers, or biotechnology—for special consideration. This theme is developed further at the conclusion of this chapter.

Facilitate Government/University/Industry Collaboration in R&D for Low-Cost Materials Manufacturing Processes

There is evidence that existing university/industry and Federal laboratory/industry joint R&D centers in advanced materials do not address the problem of commercialization of research results very effectively (see ch. 10). Rather, these programs tend to be seen by industry as promoting the infrastructure of the technology; i.e., providing access to new ideas and trained students. Although such contributions are essential and should be encouraged, it appears that a significant gap still remains between the point at which current collaborative materials R&D leaves off and the point at which industry is prepared to make significant investments to bring this R&D to commercial fruition.

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[2] *Technology and the American Economic Transition*, an upcoming OTA report.

[3] See, for instance, the report of the President's Commission on Industrial Competitiveness, "Global Competition, the New Reality," January 1985.

There are two major policy options which could help to bridge this gap.

Option 1: Establish a limited number of collaborative centers dedicated to advanced materials manufacturing technology.

Given the nature of the risks posed by manufacturing with advanced materials—very high scale-up and production costs in an uncertain market environment—it may be necessary for the government to share these costs by supporting collaborative centers designed to develop more cost-effective manufacturing methods.[4] The cost sharing could be accomplished directly through Federal matching funds, or indirectly through tax credits designed to stimulate cooperative research. These centers would not necessarily require the building of new facilities; rather, they could be based at existing centers of excellence.

There are several characteristics that such collaborative manufacturing centers should have if they are to be successful in promoting technology utilization (see ch. 10). First, the centers should incorporate the commercialization perspective into the fabric of their structure from the beginning. They should be located in settings that are very conducive to the intermingling of industry and research staff concerns. Industry should be directly involved in the planning, funding, and administration. The centers should feature direct, bench-level collaboration between visiting industrial scientists and the facility research staff. Industry managers, production engineers, and marketing personnel should have temporary assignments to work with the center staff to develop the manufacturing infrastructure needed. The centers should have ample opportunities for proprietary projects to be carried out for individual industry clients in parallel with the broader program of widely disseminated nonproprietary projects. Finally, the industry participants should commit sufficient resources to their own internal R&D efforts to be able to employ effectively the research output of the centers.

Depending on the agenda of an industry consortium aimed at developing manufacturing technology for advanced materials, there could be an antitrust conflict with the Clayton Act, Section 7 (15 U.S.C. 18). This section prohibits acquisitions and joint ventures where the effect is to lessen competition between firms. In the National Cooperative Research Act of 1984 (Public Law 98-462), the Clayton Act was amended to permit joint R&D ventures at a basic level.

Further legislation may be required to permit cooperative manufacturing development where such cooperation clearly enhances the competitiveness of U.S. industry in the global marketplace. Antitrust reform proposals along these lines are a prominent feature of the President's Competitiveness Initiative released in January 1987. Because similar consortia are now being planned in other industries, notably microelectronics, it appears unlikely that structural ceramics consortia would be the first to test this legal ground.

Option 2: Encourage large companies to work with small advanced materials firms that have manufacturing expertise but lack the capital to explore its commercial potential.

Ultimately, large integrated companies are likely to be more competitive in high volume markets for advanced materials than small companies (see ch. 9). However, the current small markets for advanced materials technologies have spawned many small materials companies that supply materials for specialty applications, especially military applications.

Like universities and Federal laboratories, these small companies represent a technology resource that could make large materials suppliers and end users more competitive in the future. Whether through acquisitions, joint ventures or other financial arrangements, large companies could use relationships with small ones to acquire access to technologies that have commercial promise, but that are not cost-effective for large companies to develop in-house.[5] Furthermore, from a national perspective, the commercialization goal may receive greater emphasis in collaborations between large and small companies than in those involving industry and academia or industry and Federal laboratories.

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[4] A similar suggestion appears in the Report of the Research Briefing Panel on Ceramics and Ceramic Composites (Washington, DC: National Academy Press, 1985).

In spite of these possible benefits, though, there is evidence to suggest that this small company resource is not receiving Federal support commensurate with its productive potential.

Executives of small materials companies contacted by OTA expressed concern that the share of Federal sources of capital going to small businesses has been declining. As shown in table 12-2, the share of Federal R&D contracts awarded to small businesses has declined since 1979, although the implementation of the Small Business Innovation Research (SBIR) program, which began in 1983, has helped to reverse this trend.[6] One reason for this decline is a trend in government procurement toward aggregating contracts into larger packages awarded to large companies that supply the overall system. Small firms involved in the government procurement process thus depend on subcontracts from the systems suppliers, rather than direct support for technology development.

A large number of small advanced materials companies have participated in the SBIR program. Those contacted by OTA have been uniformly enthusiastic about their experiences. Sources familiar with the SBIR program report that since 1982, 60 percent of Phase I awards each year have gone to firms that had no previous contact with the program.[7] This implies a geometric increase in the number of firms that have participated in the program.

Federal program managers report that they receive many more high-quality proposals than can be funded. Furthermore, they also state that they are impressed with the quality and cost-effectiveness of the research performed. This suggests that the SBIR program could be expanded without compromising the quality of the research or exhausting the supply of innovative small companies.[8]

Expanding the SBIR program is only one option for increasing the amount of capital made available for small advanced materials companies. Other alternatives could include specific provisions for reducing the cost of their participation in federally funded collaborative R&D centers, as well as encouraging prime contractors in large Federal projects involving advanced materials to subcontract more extensively to small companies.

Facilitate More Effective Commercial Exploitation of Military R&D Investments Where Possible

In the United States, the military has generally been the driving force behind the development of various kinds of composites, including those having polymer, metal, ceramic, and carbon matrices. Because of the strategic importance of some advanced materials, restrictions are placed on the dissemination of these materials and information relating to them. These restrictions tend to limit the international business opportunities of U.S.-based advanced materials companies, particularly as the advanced materials capabilities of foreign countries reach parity with those of the United States. (See ch. 11 for a discussion of the advantages and disadvantages of defense fund-

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[5] It should be noted that these small companies are a resource for large foreign companies as well as large U.S. companies, and their acquisition by foreign companies can be an important mechanism for transferring U.S. technology abroad.

[6] Enacted in 1982 (Small Business Innovation Development Act, Public Law 97-219) and phased in over 5 years, the SBIR program requires that Federal agencies with extramural R&D budgets in excess of $100 million set aside 1.25 percent of those budgets for awards to small businesses. The SBIR program is intended to meet the R&D needs of the funding agency while at the same time helping the small companies to explore avenues to commercialization of that research. It fills a unique need in the innovation process because it provides funding for the translation of a technical concept into a prototype; once the innovation has reached the prototype stage, it is expected that the small company involved will obtain additional funding from private or non-SBIR Federal sources.

[7] Ann Eskeson, President, Innovation Development Institute, personal communication, November 1987.

[8] A proposal to increase the small business set-aside from 1.25 percent to 2.5 percent is discussed in "Innovation in Small Firms," Small Business Administration Issue Alert, July 1986. Any such expansion, however, is likely to be opposed by university groups and agencies whose primary mission is to fund university research.

Table 12-2.—Share of Federal R&D Contracts Going to Small Business, 1979-86[a]

Category	Fiscal year							
	1979	1980	1981	1982	1983[b]	1984	1985	1986
Total contracts ($millions)	12,889	14,195	16,741	20,025	22,116	24,452	25,749	25,680
Small business ($millions)	846	958	987	955	1,054	1,198	1,526	1,648
Small business share (percent)	6.6	6.7	5.9	4.8	4.8	4.9	5.9	6.4
Small business share without SBIR funds (percent)	—	—	—	—	4.6	4.6	5.4	5.5

[a] Federal R&D outlays are divided roughly as follows: contracts 50%; grants 25%; and intramural 25%. Small business is defined as companies with fewer than 500 employees.

[b] Year that the Small Business Innovation Research (SBIR) program was phased in.

SOURCE: William K. Scheirer, Small Business Administration.

ing and procurement policies for advanced materials suppliers.)

As commercial applications grow and DoD becomes less of a driver and more of a consumer of advanced materials technology, the viability of the domestic industry will become the paramount consideration, from both an economic and a military point of view. To strengthen the domestic advanced materials manufacturing base, it will become more and more important to strike a balance between the competing goals of military and commercial users of ceramics and composites. If the history of the U.S. microelectronics industry is any guide, transfer of commercially developed materials and processes to the military will eventually become more important than military-to-commercial transfer.

The principal policy issues likely to be involved in developing a military/commercial balance are those associated with export controls, information controls, military research in manufacturing technologies, procurement practices, and offsets.

Export Controls

Early in 1987, the Department of Commerce proposed several changes in the administration of export controls intended to alleviate their impact on U.S. high technology trade.[9] Among these are proposals to remove from the control lists those technologies that have become available from many foreign sources, and to reduce the review period for export license applications. These changes could be helpful, but some further steps should be considered.

Option 1: Increase representation by nonmilitary materials industries (including end users) in policy planning for export controls.

Currently, policymaking decisions about export controls tend to reflect the interests of the defense community—both government personnel and defense contractors. To achieve a more balanced policy, it would help to have nondefense industry managers participate in the process.

The Department of Commerce has already taken a step in this direction, with the chartering of the Materials Technical Advisory Committee in April 1986. The purpose of the committee is to provide an industry perspective for policymakers in the materials field. When the committee has its full complement of members, the group could provide timely advice to the Department of Commerce on export control policies relating to advanced materials.

Option 2: Eliminate or loosen reexport controls.

The United States is the only country that imposes controls on the reexport by other countries of U.S.-made dual-use products (i.e., products that have both military and commercial uses), or systems that contain U.S.-made parts and components. Many countries view U.S. reexport controls as unwarranted interference in their political and commercial affairs, and this has led to a process of "de-Americanization," in which foreign companies avoid the use of U.S.-made materials and components in their systems.[10]

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[9] "Export Controls: Advancing Our National Security and Economic Vitality," *Business America*, Mar. 2, 1987.

[10] *Balancing the National Interest: U.S. National Security Export Controls and Global Economic Competition* (Washington DC: National Academy Press, 1987).

The Department of Commerce has recently revised the parts and components regulations for reexports from member countries of the Coordinating Committee for Multilateral Export Controls (CoCom), so that, for most destinations, a U.S. reexport license is needed only if U.S.-made parts and components are valued in excess of 25 percent (up from 10 percent) of the system value. This relaxation could encourage foreign companies to use more U.S.-made parts, but its effects should be assessed after a suitable period to see if it goes far enough. For shipment to proscribed countries (e.g., Eastern bloc countries), a license is required if U.S.-made parts exceed 10 percent of the system value or $10,000.

No revisions have been made in the regulations concerning reexports of stand-alone items, and a reexport license must be obtained for quantities of these items above certain threshold values. For instance, a threshold of zero applies to advanced ceramics, so that licenses are required for reexports of all advanced ceramic items. Low threshold values are used to control reexport of relatively inexpensive items that have significant military value, such as ceramic rocket nose cones. One option for encouraging foreign companies to make greater use of U.S.-made advanced materials and components would be to raise these threshold values in a product-specific way within the existing regulations.

An alternative method would be to eliminate the U.S. reexport restrictions entirely, while encouraging foreign trading partner nations to develop and maintain their own export controls for these products. In light of the recent Toshiba scandal,[11] this may be an opportune time to offer such an incentive to encourage U.S. trading partners to tighten their internal export controls.

Option 3: Streamline and coordinate the various export control lists.

All of the various lists under which technologies are controlled should receive careful review for correctness and current relevance. In particular, a better mechanism should be found for removing technologies from the lists as necessary. The Department of Commerce could be made responsible for meshing the Commodity Control List more closely with the CoCom international list and for removing outdated or widely available technologies. This review issue is important for many technologies, including advanced materials, and should be dealt with on an appropriately larger scale. However, for advanced materials in particular, reviewing the various control lists could become the responsibility of the Materials Technical Advisory Committee in the Department of Commerce.

One alternative for streamlining the advanced materials items on the control lists would be to concentrate on controlling processing technologies rather than the materials themselves. Many experts agree that because of the large number of processing variables, it is very difficult to "reverse engineer" a composite material from a chunk of the material or structure. To more effectively balance national security and commercial trade interests, it may be better to control exports of process information and loosen restrictions on material components and structures.

Option 4: Clarify the export control regulation of metal matrix composite (MMC) products and information.

At present, the Departments of Commerce and State have overlapping legal and regulatory authority to control the export of MMC technology. This arrangement is extremely confusing to U.S. companies, which have experienced long delays in obtaining approval for export licenses. In some cases, these delays have prevented U.S. MMC suppliers from establishing business relationships with foreign end users for the purpose of exploring the potential of MMC materials for commercial applications.

It would be less confusing and less time-consuming for U.S. companies to be able to deal with a single agency regulating the export of these materials and technical data. Congressional action could be appropriate to limit the control of these materials to one agency. Alternatively, the National Security Council could arbitrate a discussion between Commerce and State for the purpose of housing the control of these materials and data related to them under one roof.

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[11] Toshiba Machine Co. and a Norwegian firm, Kongsberg Vaapenfabrikk Trading Co., are charged with selling sophisticated milling equipment to the Soviet Union. This equipment may enable the Soviet Union to build quieter submarines that are more difficult to detect.

Information Controls

Technical information about advanced materials is controlled under a complex regime of laws and regulations administered by the Departments of State, Commerce, and Defense. Currently, dissemination of advanced materials technical information can be controlled via: International Traffic in Arms Regulations of the Department of State; the dual-use technology restrictions of the Department of Commerce; the Defense Authorization Act of 1984; government contract restrictions; and the government system of document classification.

There are so many ways to restrict information that actual implementation of restrictions can appear arbitrary. Under some of these laws, regulations and clauses, a company can file for a license to export, but under others, there is no mechanism to permit export of the information.

Excessive information restrictions can inhibit domestic technology development and prevent technology transfer between military and commercial applications.[12] Furthermore, they can prevent companies from becoming military contractors and also prevent military contractors from exploiting the full commercial potential of a technology. Minimizing this segregation of technology should be a goal of both the military and commercial sectors.

The present system of information controls has also led to disruption of scientific meetings and restriction of some advanced materials conference sessions to U.S.-only participation. Such U.S.-only sessions, however, can be self-defeating when—as can happen—superior technology is already available abroad. The following are two options that could help alleviate these problems.

Option 1: Simplify and clarify the various information restriction mechanisms.

One method of reducing the confusion would be to rely more on classification (the main mechanism for information control as reiterated in the President's National Security Decision Directive of 1985) and less on the other more tenuous mechanisms of control (e.g., the Defense Authorization Act and contract clauses). This would have the advantage of reducing the uncertainty that now pervades advanced materials conferences and professional societies. However, there is a trade-off between simplicity of controls, on the one hand, and flexibility on the other. If all information that is now controlled became classified, this could have the effect of making such information even less accessible.

Option 2: Make military materials databases more available to U.S. companies.

The military has a number of databases on advanced materials projects that could be made more widely available to U.S. companies. This information, now available only to defense contractors through the Defense Technical Information Center (DTIC), is more comprehensive and up-to-date than that offered by the National Technical Information Service (NTIS). DTIC contains a significant amount of information that is neither classified nor proprietary, but is still limited to registered users. Such information could be of value to U.S. commercial firms that are not government contractors.

If it is determined that it would be desirable to transfer defense databases selectively to U.S. companies, a workable definition of a U.S. company must be found. As advanced materials companies take on an increasingly international character (see ch. 9), such distinctions are becoming moot. Another alternative would be to transfer more of the DTIC databases to NTIS. However, this would make the information available to U.S. and non-U.S. companies alike.

Military Research in Manufacturing Technologies

Although military applications for advanced materials can generally tolerate higher costs for materials and processes than commercial applications, both could benefit greatly from research on low-cost manufacturing methods. The desire to reduce procurement costs led DoD to implement its Manufacturing Technologies (ManTech) program, which includes projects devoted to many different materials and manufacturing technologies.

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[12] F. Karl Willenbrock, "Information Controls and Technological Progress," *Issues in Science and Technology*, fall 1986.

Total ManTech funding for the three services plus the Defense Logistics Agency is $124 million for fiscal year 1987, with $165 million requested for fiscal year 1988. However, it is difficult to ascertain what proportion of these funds can be considered materials-related in that individual projects can be considered either as structures or materials processing efforts.

Option: Increase support for advanced materials manufacturing research through the ManTech program.

Low-cost manufacturing technologies represent a convergence of interests between DoD and the commercial sector that could hasten the commercial utilization of advanced materials technologies developed for the military. One alternative could be to augment the budget for those ManTech projects aimed at decreasing production costs and increasing reproducibility and reliability of advanced materials structures.

Procurement Practices

DoD constitutes a special market with unique materials requirements. However, like other customers for advanced materials, DoD strives to have the widest variety of materials available at the lowest possible cost. Therefore, it employs regulatory means to simulate the conditions of commercial markets. This makes the participation by materials suppliers extremely dependent on defense regulations and policies, rather than on conventional economic criteria. Through its policies on dual sourcing, materials qualification, and domestic sourcing of advanced materials, DoD has a profound influence on the cost and availability of a variety of high-performance materials and technologies.

Option: Provide a clear plan for implementing domestic sourcing regulations for advanced materials.

Carbon fibers used in advanced composites provide a useful example of the need for a clear plan for implementing domestic sourcing policies. Most high-performance carbon fiber is derived from an organic precursor material called polyacrylonitrile (PAN). Although there are many companies in the United States that are capable of manufacturing carbon fiber from PAN, 100 percent of PAN precursor for composites qualified for U.S. military use is imported. At present, Amoco is the only domestic producer of PAN precursor; however, Amoco's carbon fibers are still undergoing qualification testing.

In the Defense Appropriations Act of 1987 (Public Law 100-202) Congress specified that 50 percent of all defense requirements for PAN-based carbon fiber be produced domestically by 1992.[13] Congress has required that DoD provide a program plan to fulfill this PAN requirement; the plan is due to be presented in June 1988.[14]

A prior DoD directive on domestic sourcing of PAN requires two or more domestic suppliers. Such suppliers would not have to be U.S.-owned as long as their plants are located in the United States.

Domestic suppliers of carbon fiber made from imported PAN welcome this legislation, but they are uncertain about how it will be implemented, and about which weapon systems would be involved.

To make intelligent investment decisions, U.S. carbon fiber suppliers would like DoD to provide a comprehensive plan for implementing the proposed directive. The greater the percentage of domestic PAN precursor used in military systems, the more attractive it will be to invest in the opening of a plant; the proposed requirement of 50 percent by 1992 is considered very appealing by industry.

To be effective, the program plan must specify which weapons systems will be required to use domestically produced PAN and in what quantities. In addition, industry would like assurances that domestically produced PAN will be procured even if foreign-produced PAN is initially less expensive. It would also be necessary for DoD to guarantee to purchase minimum quantities of the fiber in order for industry to establish new production facilities.

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[13] *Congressional Record*, Dec. 12, 1987, vol. 133, No. 205, part III, pp. H12546-7.

[14] Ken Foster, U.S. Department of Defense, personal communication, May 7, 1987.

Offsets

Offsets are a foreign policy-related marketing device that can be detrimental to the U.S. advanced materials technology base. Technology offsets are commonly required by foreign customers before they will consider bids from U.S. or other systems suppliers. In recent years, little attention has been paid to the effects of offsets.

It appears that the best way to prevent the distribution of U.S. advanced materials technology through offsets is to prevent foreign nations from requiring offsets from U.S. companies. Perhaps this is best addressed in the context of trade negotiations on specific systems, such as military and commercial aircraft. However, offsets are only a small part of such trade negotiations, and foreign policy goals may preempt this approach. This issue is of increasing importance to materials suppliers as foreign nations become more and more interested in acquiring U.S. technology and competing in U.S. markets.

Option: Initiate a thorough study of the effects of offsets on the competitiveness of U.S. advanced materials industries.

Build a Strong Advanced Materials Technology Infrastructure

For U.S. advanced materials suppliers and users to rapidly exploit materials technology developments over the long term, whether these developments occur within the United States or abroad, a strong U.S. technology infrastructure must be built to support the cost-effective use of the new materials. Such an infrastructure would include the availability of basic scientific knowledge, technical data to support design and manufacture, and an adequate supply of trained personnel. Infrastructure investments are generally considered the responsibility of the Federal Government, since they are a public good, i.e., they cannot be appropriated for an individual company's benefit. There are several policy options to be considered as a means of supporting the development of a strong technology infrastructure.

Option 1: Increase the funding for R&D in advanced materials and their manufacturing processes to reduce costs and increase reliability and performance.

Although ceramics, polymer matrix composites, and metal matrix composites technologies are at different stages of maturity and have different applications, there are four R&D priorities common to all three technologies:

1. Manufacturing science research is needed to support the development of cost-effective manufacturing processes.
2. The relationships between structure, mechanical properties, and failure mechanisms must be understood to take advantage of the anisotropic properties of advanced materials.
3. The behavior of advanced materials in severe environments must be determined to facilitate reliable design and life prediction.
4. The interfacial region between matrix and reinforcement in composites, which has a critical influence on composite behavior, must be properly understood.

These priorities are widely appreciated, and OTA finds that current agency R&D programs are generally consistent with them. However, greater funding in these priority areas could accelerate commercial use of advanced materials. Alternatively, if overall funding is reduced, preservation of funding in these areas should be a priority.

Option 2: Develop a comprehensive account of collaborative R&D efforts in advanced materials at the Federal, regional, and State levels, including program goals and funding.

Collaborative R&D programs promise to spread the risks of industry investments in advanced materials. Numerous centers of excellence focusing on various aspects of advanced materials technologies have been initiated in the past several years, and little attention has been paid to wasteful overlap or the possibility of exhausting common sources of funding.

The ad hoc process by which collaborative centers are currently established has both advantages and disadvantages. The principal advantage is that many different competing organizational models can be explored, leading to a Darwinian "survival of the fittest." This approach also fosters more diverse solutions to technological problems, as well as providing broader educational opportunities for students.

One of the disadvantages is that the resulting dispersion of talent and resources could prevent a coalescing of all the factors necessary to create a first class advanced materials industry.[15] This especially appears to be a problem with advanced materials, in which design, processing, and testing are so closely integrated. The best solution may be a mix of small, dispersed centers with a limited number of larger, integrated centers in which design, processing, and evaluation are undertaken under one roof.

A comprehensive account of collaborative R&D efforts in advanced materials would be a necessary first step in drawing lessons from experience with various collaborative models, and in minimizing wasteful duplication of effort. It would not be appropriate for the Federal Government to attempt to discourage States from establishing collaborative centers of excellence in any technology. However, to the extent that Federal funding is sought by these centers, the government could use its leverage to encourage them to work together as much as possible. New Federal centers should only be undertaken after taking into account the existing context of State and regional centers.

The Omnibus Trade and Competitiveness Act of 1987 (H.R. 3) contains a provision to create a central clearinghouse within the Department of Commerce's Office of Productivity, Technology, and Innovation to keep track of State and regional competitiveness initiatives, including collaborative centers. Such a clearinghouse could be the vehicle for gathering information on advanced materials centers. Alternatively, an organization such as the National Critical Materials Council could undertake to gather this information.

Option 3: Gather comprehensive information on current activities in government-funded advanced materials R&D.

One persistent need identified by many industry sources is information on the many different government activities in advanced materials. In general, this information exists but is rarely in a form readily accessible to researchers. A database could be assembled containing a listing of projects by subject and sponsoring agency, each entry accompanied by the name of a contact, annual budget, milestones achieved, bibliography of project reports, and technology transfer activities. Some of the specific benefits of such a database would include:

- A point of access for those interested in perusing recent reports or those seeking information on current programs in an area of interest.
- A source for tracing trends in funding and priorities for materials science and engineering over time.
- A source for assessing the effectiveness of government-to-industry technology transfer efforts in materials.

The preparation of such a database would not be difficult, as most of the information exists in various forms in the funding agencies.[16] Such a project would be consistent with the mandate of the National Critical Materials Council. The Council could work with other government groups such as the Center for the Utilization of Federal Technologies at the National Technical Information Service (NTIS), and it could also oversee the annual updating of the database by tapping program managers in the various Federal agencies involved.

Option 4: Establish a mechanism for gathering business performance statistics for advanced materials industries.

It is very difficult to obtain accurate, up-to-date business statistics on advanced materials production, imports, and exports. The Standard Industrial Classification categories now in use do not distinguish these advanced materials from conventional materials. For instance, advanced ceramics are aggregated together with ceramic tableware and sanitary ware. This situation contrasts sharply with that in Japan, where each month the Ministry of International Trade and Industry publishes detailed statistics on the production and export of advanced ceramics broken out by product type. Such statistics are extremely useful in understanding production trends and in assessing the competitive status of the U.S. advanced materials industries.

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[15] R.M. Latanision, "Developments in Advanced Materials in the Industrialized Countries," proceedings of the Federation of Materials Societies' Ninth Biennial Conference on National Materials Policy, Fredericksburg, VA, August 1986. p. 21.

[16] Such a database collected on government funding of structural ceramics in 1985 was used in table 3-11 to compare the recommended R&D priorities for structural ceramics with actual agency spending.

Proposals to revise SIC codes to take account of advanced ceramics industries have been under study since 1985 by the United States Advanced Ceramics Association.[17] However, this issue has not received a high priority within the industry, and no action is currently contemplated. This may turn out to be a short-sighted decision. As international trade in advanced materials and components grows, these statistics could also provide the documentation required to prove damage to domestic ceramics industries from unfair trading practices abroad.[18]

Option 5: Increase funding for person-to-person efforts to gather and disseminate data on international developments in advanced materials.

The cultural and scientific parochialism of Americans has been widely recognized, and there have been many calls for programs to gather technical data from abroad and to translate foreign technical publications into English.[19] As several countries approach and exceed U.S. capabilities in advanced materials technologies, it becomes imperative for U.S. companies to have access to such information. Particularly acute is the lack of qualified translators who also have a technical background. The establishment of first-class technology information networks worldwide is one of the strengths of Japan, a principal economic competitor of the United States.

The Federal Government currently has several scattered programs to address this problem. In 1986, Congress passed the Japanese Technical Literature Act (Public Law 99-382), which reallocated $1 million within the Department of Commerce for assessing and monitoring Japanese technical publications. Other Federal programs include the National Science Foundation's (NSF) JTECH reports, which provide an assessment of Japanese efforts in various technical areas.[20]

The Federal Government's efforts to gather technical data are hampered by several factors. One is that the demand for such information is not very well defined. Not everyone has a desire or need for the same data, making it difficult to select a commonly agreed upon subset of available data for translation. Critics of translation programs argue that the most useful information is obtained through informal discussions of ongoing work, rather than through publications, which may contain data more than a year old. Another factor is that large companies tend to rely on their own data-gathering mechanisms, which smaller companies cannot afford. In addition, many private firms offer data-gathering and translation services in foreign countries for sale to other parties.[21] Federal Government translation programs thus risk competing with the private sector.

A policy alternative to massive government translation of foreign technical articles would be to recognize the importance of person-to-person contact in technology exchange. Congress could mandate that increased funding be provided for exchange programs, travel to international scientific meetings by U.S. scientists, language training for U.S. science graduate students, and sabbaticals abroad for U.S. technical personnel. Such funding is essential for U.S. visitors to Japan, for instance, where the national laboratories do not provide funds to cover the salaries of visiting scientists, and where postdoctoral fellowships are not available. In addition, U.S. beneficiaries of these programs should be encouraged to publish accounts of their experiences, and to disseminate this information to U.S. industry.

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[17] A similar option is proposed in "A Competitive Assessment of the U.S. Advanced Ceramics Industry," NTIS PB84-162288, Department of Commerce, March 1984.

[18] Michael T. Kelley, Department of Commerce, personal communication, August 1987.

[19] For a review see "Monitoring Foreign Science and Technology for Enhanced International Competitiveness: Defining U.S. Needs," the proceedings of a workshop conducted by the Office of Naval Research and the National Science Foundation, Washington, DC, October 1986.

[20] See, for instance, Science Applications International Corp., "JTECH Panel Report on Advanced Materials in Japan," JTECH-TAR-8502, a contractor study prepared for the National Science Foundation, May 1986.

[21] One such firm is the Japan Technical Information Service of University Microfilms International, located in Ann Arbor, MI.

Option 6: Increase support for the development of standards for advanced materials.

Standardization, particularly the need for standard test methods, has long been identified as an important priority for advanced materials (see ch. 5). The problems inherent in setting standards in rapidly moving technologies are clear. Standards development is a consensus process that takes years, and it is all the slower with advanced materials because of their complex and unfamiliar behavior. However, tackling the standards problem now rather than later could not only speed the development of the technologies, but also enhance the future competitiveness of U.S. advanced materials companies.

There are already international organizations that are pursuing advanced materials standards. Among these are the Versailles Project on Advanced Materials and Standards (VAMAS), with projects in 13 materials areas, and the International Energy Agency which is focusing on characterization of ceramic powders and materials. Currently, U.S. participation in these international standards-related activities tends to be part-time, with funds set aside from other budgets. Provision of separate funds for VAMAS liaison and international travel for the U.S. officials involved could make U.S. representation more effective.

Although U.S. participation in these international efforts is likely to be important, it will also be essential to develop domestic standards for advanced materials. Standards implicitly reflect the domestic capabilities of the originators, including specialized equipment and expertise. Having viable domestic standards would thus not only help U.S. industry to capitalize on domestic practices and capabilities but would also serve as a basis for negotiations on international standards.

Among the United States' foreign competitors, Japan appears to be making the largest overall effort in ceramics standards. Japan is actively seeking to establish international standards, and would prefer that those international standards resemble Japan's domestic standards as closely as possible—just as U.S. ceramics companies would prefer that those standards be close to U.S. domestic standards.

The principal disadvantage stemming from U.S. adoption of Japanese standards would be the loss of time involved with compliance. Moreover, Japan's quality control standards already allow the Japanese to produce ceramics at a lower cost. The rejection rate for final ceramic products, a major factor determining overall production costs, is significantly lower in Japan than in the United States.[22]

Option 7: Increase the pool of trained materials scientists and engineers by providing increased funding for multidisciplinary university programs in advanced structural materials and by providing retraining opportunities for technical personnel in the field.

To take advantage of the opportunities presented by advanced materials, the United States must maintain a viable population of trained materials scientists and engineers. Industrial sources contacted by OTA were nearly unanimous in their recommendation that more trained personnel are needed. Because materials science and engineering cut across many traditional academic disciplines, it will be essential to train students in multidisciplinary programs. This training should prepare them to take a systems approach in designing and manufacturing with advanced materials (see ch. 5).

Another important source of manpower is likely to result from the retraining in the field of designers and manufacturing engineers who are unfamiliar with the new materials. Small businesses, professional societies, universities, and Federal laboratories could all play a role in providing such retraining services.

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[22] Steve Hsu, Chief, Ceramics Division, National Bureau of Standards, personal communication, November 1987.

TWO VIEWS OF ADVANCED MATERIALS POLICIES

Congress and the Reagan Administration have adopted conflicting views of policymaking with respect to advanced materials. In the congressional view, the Federal Government should formulate a high-level national plan for advanced materials research, development, and technology, whereas in the Administration's view, such goals and priorities should be established in a decentralized fashion by the principal funding agencies according to their various missions.

As indicated in table 12-3, Congress has long been concerned with materials issues, dating back to the Strategic War Materials Act of 1939 (53 Stat. 811). Through the 1950s, congressional legislation continued to focus on ensuring access to reliable supplies of strategic materials in time of national emergency. The 1970s saw congressional interest broaden to include the economic and environmental implications of the entire materials cycle, from mining to disposal. In Title II of the Resource Recovery Act of 1970 (Public Law 91-512), Congress called upon the executive branch to develop a comprehensive national materials policy relating to materials supply, use, recovery, and disposal. The Act authorized the National Commission on Materials Policy to identify national materials requirements and priorities, enhance coordination among Federal agencies' materials activities, and assign responsibilities for the implementation of national materials policy.

The National Materials and Minerals Policy, Research, and Development Act of 1980 echoed these themes, noting that the United States lacks a coherent national materials and minerals policy. It called on the President to coordinate Federal efforts to identify and assess materials needs for commerce, the economy, and national security. It also mandated that the President submit to Congress a program plan outlining mechanisms for responding to these needs.

Table 12-3.—U.S. Materials and Minerals Legislation

Strategic War Materials Act—1939
53 Stat. 811
Established the National Defense Stockpile, intended to accumulate a 5-year supply of critical materials for use in wartime or national emergency.

Strategic and Critical Materials Stockpiling Act—1946
60 Stat. 596
Authorized appropriation of money to acquire metals, oils, rubber, fibers, and other materials needed in wartime.

Defense Production Act—1950
64 Stat. 798
Authorized President to allocate materials and facilities for defense production, to make and guarantee loans to expand defense production, and to enter into long-term supply contracts for scarce materials.

Resource Recovery Act—1970
Public Law 91-512
Established the National Commission on Materials Policy to develop a national materials policy, including supply, use, recovery, and disposal of materials.

Mining and Minerals Policy Act—1970
Public Law 91-631
Encouraged the Secretary of the Interior to promote involvement of private enterprise in economic development, mining disposal, and reclamation of materials.

Strategic and Critical Stockpiling Revision Act—1979
Public Law 96-41
Changed stockpile supply period to 3 years, limited to national defense needs only; established a stockpile transaction fund.

National Materials Policy, Research and Development Act—1980
Public Law 96-479
Directed the President to assess material demand, supplies, and needs for the economy and national security, and to submit a program plan to implement the findings of the assessment.

National Critical Materials Act—1984
Public Law 98-373
Established the National Critical Materials Council in the Executive Office of the President; the Council was authorized to oversee the development of policies relating to both critical and advanced materials; and to develop a program for implementing these policies.

SOURCE: Office of Technology Assessment, 1988.

In 1984, Congress explicitly extended these concerns to cover advanced materials with the passage of the National Critical Materials Act (Public Law 98-373, Title II). In this Act, Congress established the National Critical Materials Council (NCMC) in the Executive Office of the President and charged it with the responsibility of overseeing the formulation of policies relating to both critical minerals and advanced materials. The intent was to establish a policy focus above the agency level to set responsibilities for developing materials policies, and to coordinate the materials R&D programs of the relevant agencies. The NCMC is also directed to establish a national Federal program plan for advanced materials R&D.

Thus, the idea of a national materials policy for advanced materials is an extension of policy goals already articulated for a broad class of materials considered critical for the economy and national defense. Implicit in the congressional view is that national goals and priorities for advanced materials can be identified as readily as those for more traditional critical materials. According to this view, such goals and priorities should be established above the agency level, and agency spending on materials programs should be made consistent with them.

The United States has long had a decentralized approach to advanced materials policy. To a great extent, the major agencies that engage in materials R&D—DoD, DOE, NASA, and NSF—sponsor projects according to their distinct missions. In the congressional view, the growing technological capabilities of overseas competitors have underscored the urgency of establishing a nationally coordinated approach to advanced materials development. Advocates of a national materials policy point to the apparent capacity of Japan to identify key technologies for the future and pursue their development in a coordinated, government-industry effort, as has already occurred in Japan in advanced ceramics.

In the Administration's view, it is not appropriate for the Federal Government to engage in strategic advanced materials planning. Such planning would constitute putting the government in a position of "picking winners"—which, according to current Administration thinking, is best left to the private sector. Because different agencies have different missions and requirements for materials, the determination of R&D priorities is best made at the agency level. Administration critics of the national materials policy concept maintain that attempts to make materials policy above the agency level risk the worst aspect of Japanese policies—the creation of an overbearing bureaucracy—without achieving the best effect, which is the commitment and coordination of industry.

Although the materials requirements of different government agencies are diverse, meetings among agency managers of programs involving advanced materials are fairly frequent. In fact, several government committees meet to exchange information about ongoing advanced materials projects. These include the Committee on Materials (COMAT), within the White House Office of Science and Technology Policy; the Interagency Materials Group hosted by NSF; and the Interagency Coordinating Committee for Structural Ceramics, which has a rotating chairmanship. A variety of coordinating groups also exist within various agencies, such as the Energy and Materials Coordinating Committee in the DOE. In the Administration's view, information shared through COMAT and the other interagency materials committees is adequate to avoid excessive duplication and waste in Federal materials R&D programs. Therefore, the congressionally mandated NCMC is considered redundant.

While the Administration has resisted the concept of strategic advanced materials planning for commercial competitiveness, it has embraced it with regard to national defense needs. DoD is currently preparing a comprehensive policy initiative aimed at preserving the U.S. defense industrial base. This initiative will target for support a portfolio of technologies, including machine tools, bearings, castings, semiconductors, and advanced composites. In addition, it will address such issues as technological obsolescence, availability of trained personnel, foreign acquisitions of U.S. companies, international cooperation, and government/university/industry collaboration.[23]

The congressional and Administration views reflect different philosophies regarding the appropriate Federal and private sector roles in technology planning and development. These two views are not easily reconciled. However, if some of the debate can be clarified, common ground may emerge. Much of the confusion has to do with exactly what is meant by a "national materials policy."

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[23] Robert Costello, Department of Defense, in a presentation to the annual meeting and industry conference of the Suppliers of Advanced Composite Materials Association, Arlington, VA, May 5-8, 1987.

There are several problems in defining the concept of a national materials policy clearly. One is that the scope of materials science and technology is extremely broad; even the rubric of "advanced materials" includes structural, electronic, optical, magnetic, and superconducting materials technologies. These technologies all have different levels of maturity and applications. This diversity cannot be fully addressed in the context of a single policy.

A further problem is that the policy considerations appropriate to various types of materials may be very different. Whereas policy goals such as conservation of scarce materials or reliable access to strategic minerals are easily understood in the context of conventional materials, it is much more difficult to define national goals for advanced materials. Advanced materials technologies tend to be application-driven, with specific performance requirements determined by specific applications. For instance, the cost and performance requirements of a ceramic tile for the space shuttle are very different from those of a ceramic diesel engine.

Perhaps the first steps toward a national policy would be to identify those materials (e.g., advanced ceramics) that may be regarded as especially promising, and to make the determination that a strong domestic fabrication capability is a national goal. The next step could be to identify and pursue—in consultation with industry—generic cost and performance objectives (strength, reproducibility, etc.) that will be required for the material to compete in a large number of products and processes. Japan's Ministry of International Trade and Industry has used this approach successfully in its collaborative ceramics programs with Japanese industry.[24] Alternatively, large demonstration programs could be undertaken that require major development and use of new materials. However, unless the end product of such a demonstration program is something that industry wants to commercialize, the program may not result in significantly greater commercial use of the materials.

A national policy approach to advanced materials is likely to have several potential advantages. First, it could provide a focus for the efforts of individual agencies and collaborative government/industry projects. Second, it could provide continuity of funding in a given area as fashionable R&D areas change from year to year. Third, it could provide a rationale for committing large amounts of resources for expensive demonstration programs. To be successful, such a national program should be structured with consultation and participation of academia, the Federal laboratories, and the industry community that will ultimately implement it.

Such a national approach also has several potential disadvantages. First, it may focus on the wrong materials and be too inflexible to capitalize on new opportunities that arise. Second, it may tie up resources and manpower in long-term projects that are better invested elsewhere. Third, because it cannot address the actual cost and performance requirements of materials in commercial markets, it may fail to produce materials or processes that are economically attractive to U.S. industry.

An alternative approach would be to enhance the present decentralized policy. The decentralized approach permits maximum flexibility of response to rapidly changing technologies and applications, and support for the broadest range of new materials technologies. One potential disadvantage of this approach is that the overall effort could be too fragmentary to bring together the critical mass of talent and resources necessary to solve the most difficult problems. This situation is particularly serious when investment risks are high, when the resources required are substantial, and when it is difficult for private companies to appropriate the full benefits of their investments. For instance, these conditions appear to apply to the development of more cost-effective advanced materials manufacturing technologies.

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[24] National Materials Advisory Board, *High Technology Ceramics in Japan*, NMAB-418 (Washington, DC: National Academy Press, 1984).

In such cases, collaborative efforts involving government, university, and industry participants are necessary to enhance the decentralized approach. Another critical requirement of this approach is continuous exchange of information among government agencies and industries involved in advanced materials R&D. This is necessary to ensure against excessive duplication of effort and to select for the highest quality research. Specific policy options for promoting more effective government/university/industry collaboration and information exchange are discussed above.

The Critical Materials Act of 1984 invests the responsibility of developing a national materials program plan in the NCMC. To succeed in this task, the NCMC will need to establish a more precise definition of the goals that would motivate such a national plan, as well as to develop high-level Administration commitment to the concept of a national materials policy. At present, Congress and the Reagan Administration remain far apart in their views of the appropriate scope of a national materials program plan, and of the role of the NCMC. Pending the resolution of these differences, there are three further functions that the NCMC could perform:

1. *Serve as a point of contact to receive and monitor industry concerns relating to advanced materials.* An organization such as the NCMC could provide forums for interaction between industry and the Federal Government on issues relating to advanced materials, particularly those that transcend the purview of any one agency. These forums could promote better mutual understanding of government and industry perspectives on advanced materials development, and they could eventually lead to the development of a consensus on promising future directions.
2. *Serve as a source of information and referral regarding advanced materials.* U.S. advanced materials programs and expertise are widely dispersed throughout various Federal agencies and laboratories. There is currently no definitive source of information that would provide an overview of ongoing efforts. An organization such as the NCMC could gather this information from the relevant agencies, analyze it, and disseminate it. Examples of the kinds of information desired include data on advanced materials projects in Federal laboratories, agency budgets for advanced materials, data on collaborative materials R&D at both Federal and State levels, industry performance statistics, and foreign materials R&D developments.
3. *Serve as a broker for resolving conflicts between military and commercial agency goals for advanced materials.* Some materials issues transcend individual agencies and therefore could be addressed most effectively by an organization operating above the agency level. For instance, the export control regime for regulating advanced materials and information relating to them is spread over the Departments of Commerce, State, and Defense, creating a situation that is very confusing to U.S. industry (see ch. 11). An organization such as the NCMC could work with the National Security Council to help simplify and clarify the three agencies' responsibilities.

ADVANCED MATERIALS POLICIES IN A BROADER CONTEXT

For U.S. industry, the risks of commercial investments in new structural materials technologies are great in the current business environment; however, the risks of failing to invest could be much greater. In the near term, there is little money to be made from such investments. The extent to which government and industry can cooperate in reducing or spreading these risks will have much to do with future U.S. competitiveness in advanced materials technologies.

In many respects, the competitive challenges facing advanced materials companies are a microcosm of the challenges facing the U.S. manufacturing sector as a whole. Therefore, advanced materials policy cannot be discussed in a vacuum.

Objectively, there is no more justification for the NCMC than for a national microelectronics council or a national biotechnology council. Moreover, policy options such as tax incentives for long-term capital investments or revising export controls could serve to stimulate a broad range of technologies, not just advanced materials.

Such far-reaching policies cannot be initiated at the agency level or in interagency committees; they clearly must be initiated in the highest councils of government. Advanced materials policies, therefore, can most effectively be addressed as one facet of a high-level, high-priority policy of strengthening the Nation's entire industrial and manufacturing base.

Appendixes

Appendix A

Contractors and Workshop Participants

CONTRACTORS

P. Beardmore
C.F. Johnson
G.G. Strosberg
Ford Motor Co.
Dearborn, MI

John Busch
Frank Field
Materials Modeling Associates
Massachusetts Institute of Technology
Cambridge, MA

Business Communications Co.
Norwalk, CT

Dale E. Chimenti
Thomas J. Moran
Joseph A. Moyzis
Air Force Materials Laboratory
Wright Patterson AFB, OH

J.D. Eveland
Cognos Associates
Palo Alto, CA

Steven R. Izatt
PA Consulting Group
Hightstown, NJ

R. Nathan Katz
Alfred L. Broz
Army Materials Technology Laboratory
Watertown, MA

D.B. Marshall
Rockwell International Science Center
Thousand Oaks, CA

J.J. Mecholsky
The Pennsylvania State University
State College, PA

Kenneth L. Reifsnider
Virginia Polytechnic Institute and State University
Blacksburg, VA

David W. Richerson
Ceramatec
Salt Lake City, UT

J.E. Ritter
University of Massachusetts
Amherst, MA

Elaine P. Rothman
Massachusetts Institute of Technology
Cambridge, MA

Julie M. Shoenung
Joel P. Clark
Massachusetts Institute of Technology
Cambridge, MA

Trudy Solomon
Solomon Associates
Bethesda, MD

Reginald B. Stoops
R.B. Stoops & Associates
Newport, RI

Strategic Analysis, Inc.
Reading, PA

Technology Management Associates
Chevy Chase, MD

Louis Tornatzky
Industrial Technology Institute
Ann Arbor, MI

Carl Zweben
General Electric Co.
Philadelphia, PA

PROJECT WORKSHOPS (Listings of Participants Follow)

Ceramics Workshop Participants, Nov. 14-15, 1985

Composites Workshop Participants, Nov. 21-22, 1985

Future Applications of Ceramics Workshop Participants, Dec. 9, 1985

Future Applications of Composites Workshop Participants, Dec. 10, 1985

International Competitiveness Workshop Participants, Dec. 15-16, 1986

Government/University/Industry Collaborations Workshop Participants, Jan. 12, 1987

WORKSHOPS

Ceramics Workshop Participants
Nov. 14-15, 1985

Alfred Broz
Army Materials Technology Laboratory
Watertown, MA

Joel Clark
Massachusetts Institute of Technology
Cambridge, MA

Tom Henson
GTE Products
Towanda, PA

R. Nathan Katz
Army Materials Technology Laboratory
Watertown, MA

Jack Mecholsky
Pennsylvania State University
State College, PA

David Richerson
Ceramatec Inc.
Salt Lake City, UT

John Ritter
University of Massachusetts
Amherst, MA

Elaine Rothman
Massachusetts Institute of Technology
Cambridge, MA

Composites Workshop Participants
Nov. 21-22, 1985

Joel Clark
Massachusetts Institute of Technology
Cambridge, MA

John DeVault
Hercules Aerospace Co.
Salt Lake City, UT

Thaddeus Helminiak
Wright-Patterson AFB
Dayton, OH

Joseph Moyzis
Wright-Patterson AFB
Dayton, OH

Kenneth Reifsnider
Virginia Polytechnic Institute
Blacksburg, VA

Reginald Stoops
R.B. Stoops & Assoc.
Newport, RI

Charles L. Tucker
University of Illinois
Urbana, IL

Carl Zweben
General Electric Co.
Philadelphia, PA

Future Applications of Ceramics Workshop Participants
Dec. 9, 1985

Charles Berg
Northeastern University
Boston, MA

Bill Kuhn
Zesto-Therm
Cincinnati, OH

Albert Paladino
Advanced Technology Ventures
Boston, MA

Rustum Roy
Pennsylvania State University
State College, PA

Jim Wimmer
Garrett Turbine Engine Co.
Phoenix, AZ

Future Applications of Composites Workshop Participants
Dec. 10, 1985

Charles Berg
Northeastern University
Boston, MA

Bob Hammer
Boeing Commercial Aircraft Co.
Kirkland, WA

D. William Lee
Arthur D. Little, Inc.
Cambridge, MA

Joe Lees
DuPont Co.
Wilmington, DE

Paul McMahan
Celanese Research Corp.
Summit, NJ

Darrell H. Reneker
National Bureau of Standards
Gaithersburg, MD

John Riggs
Celanese Research Corp.
Summit, NJ

Charles Segal
Omnia
Raleigh, NC

International Competitiveness Workshop Participants
Dec. 15-16, 1986

Stanley Abkowitz
Dynamet Technologies, Inc.
Burlington, MA

David Allen
Allied Signal Corp.
Morristown, NJ

E. Reed Bell
Shell Chemical Co.
Houston, TX

James N. Burns
Hercules, Inc.
Magna, UT

David Cammerota
U.S. Department of Commerce
Washington, DC

John A. Coppola
Standard Oil Engineered Materials Co.
Niagara Falls, NY

Samuel J. Dastin
Grumman Aircraft Systems
Bethpage, NY

Joseph F. Dolowy
DWA Composite Specialities, Inc.
Chatsworth, CA

Scott Farrow
Carnegie Mellon
Pittsburgh, PA

R. Wayne Godwin
BASF Corp.
Charlotte, NC

A. Seth Greenwald
Mount Sinai Medical Center
Cleveland, OH

Michael T. Kelley
U. S. Department of Commerce
Washington, DC

Robert Manildi
Hexcel Corp.
Dublin, CA

James Manion
U.S. Department of Commerce
Washington, DC

Paul Pendorf
ICI Fiberite
Orange, CA

Randolph B. Robinson
Manager, Technical Engineering
Beech Aircraft Corp.
Wichita, KA

Robert Russell
Norton Company
Northboro, MA

John Scanlon
U.S. Army Corps of Engineers
Vicksburg, MS

Moira Shea
U.S. Department of Commerce
Washington, DC

Nicholas Spencer
Ciba-Geigy Corp.
Fountain Valley, CA

Dick J. Wilkins
University of Delaware
Newark, DE

David Wirth
Coors Ceramics Co.
Golden, CO

Government/University/Industry Collaborations Workshop Participants
Jan. 12, 1987

Michael G. Bolton
Lehigh University
Bethlehem, PA

Ed Cohen
New Jersey Science and Technology Commission
Trenton, NJ

Dan Dimancescu
Technology and Strategies Group
Cambridge, MA

Henry Etzkowitz
Rensselaer Polytechnic Institute
Troy, NY

Robert M. Fisher
Lawrence Berkeley Laboratories
Berkeley, CA

Sarah Shauf Friel
Centocor, Inc.
Malvern, PA

Robert E. Gee
Midwest Technology Development Institute
St. Paul, MN

Carmela Haklisch
Rensselaer Polytechnic Institute
Troy, NY

Steven Hsu
National Bureau of Standards
Gaithersburg, MD

Bernard H. Kear
Rutgers University
Piscataway, NJ

Ronald Latanision
Massachusetts Institute of Technology
Cambridge, MA

Samuel Thomas Picraux
Sandia National Laboratory
Albuquerque, NM

Dwight A. Sangrey
Rensselaer Polytechnic Institute
Troy, NY

Warren D. Siemens
Martin-Marietta Energy Systems
Oak Ridge, TN

Thomas Rhyne
Microelectronics and Computer Technology Corp.
Austin, TX

Amy L. Walton
Jet Propulsion Laboratories
Pasadena, CA

OUTSIDE REVIEWERS

Stanley Abkowitz
Dynamet Technologies, Inc.

Craig Ballinger
Federal Highway Administration

Gregory B. Barthold
Aluminum Co. of America

E. Reed Bell
Shell Chemical Co.

Arden Bement
TRW, Inc.

William Bennett
AMOCO

William Broatch
NARMCO Materials

Henry Brown
Society for the Advancement of Materials and Process Engineering

Stephen D. Bryen
U.S. Department of Defense

Harris Burte
Air Force Materials Lab

Stan Channon
Private Consultant

Ed Cohen
New Jersey Science and Technology Commission

Dan Cook
U.S. Department of Commerce

Harry Cook
Chrysler Motors Corp.

Leslie G. Cooke
Hysol-Grafil Inc.

Dominique Cotto
Embassy of France

Anthony Cox
Embassy of Great Britain

Sam Dastin
Grumman Aircraft Systems

Dick Dauksys
Hexcel Corp.

Vince Decain
U.S. Department of Commerce

Raymond F. Decker
University Science Partners, Inc.

Wim van Deelen
Delegation of the Commission of European Communities

Gail DiSalvo
Ciba-Geigy Corp.

Joe Dolowy
DWA Composite Specialties, Inc.

Mike Dowell
Union Carbide Corp.

Donald E. Ellison
Donald Ellison & Associates, Inc.

Henry Etzkowitz
Rennselaer Polytechnic Institute

Renee G. Ford
MIT Press

David Forest
Ferro Corp.

Kenneth Foster
U.S. Department of Defense

Sarah Shauf Friel
Centocor, Inc.

I. Freund
U.S. Polymeric

Geoffrey Frohnsdorff
National Bureau of Standards

Robert E. Gee
Midwest Technology Development Institute

Harold Gegel
Wright-Patterson Air Force Base

Louis A. Gonzalez
Metal Matrix Composite Information Analysis Center

Robert J. Gottschall
U.S. Department of Energy

Michael Greenfield
National Aeronautics and Space Administration

Don Gubser
Naval Research Lab

Tim Gutowski
Massachusetts Institute of Technology

Carmela Haklisch
Rensselaer Polytechnic Institute

Richard Helmuth
Portland Cement Association

Robert Katz
Army Materials Technology Laboratories

Joe Jackson
Suppliers of Advanced Composite Materials Association

Manfred Kaminsky
Surface Treatment Science International

Charles Kaufmann
American Cyanamid

Mike Kelley
U.S. Department of Commerce

Joseph Kirkland
E.I. du Pont de Nemours & Co.

Glenn Kuebeler
Hercules Aerospace Co.

Bernard Levy
Inland Steel Research Laboratories

Emile G. Louzada
Netherlands Embassy

Bernard Maggin
National Research Council

Robert Manildi
Hexcel Corp.

Dick McLane
Boeing Commercial Airplane Co.

Bruce Merrifield
U.S. Department of Commerce

Robert Murphy
BASF Structural Materials, Inc.

Seymour Newman
Ford Motor Co.

Chuck Northrup
Strategic Defense Initiative Office

Paul Pendorf
ICI Fiberite

Jerome Persh
U.S. Department of Defense

John Quinlivan
Boeing Commercial Airplane Co.

Darrell Reneker
Office of Science and Technology Policy

Thomas Rhyne
Microelectronics & Computer Technology Corp.

William C. Riley
Research Opportunities, Inc.

Maxine Savitz
Garrett Corp.

Lyle Schwartz
National Bureau of Standards

Roger Seifried
Cincinnati Milacron

Moira Shea
U.S. Department of Commerce

Jacques Shouttens
Metal Matrix Composite Information Analysis Center

J. Nicholas Spencer
Ciba-Geigy Corp.

Jim Stephan
Coors Biomedical

Charles West
Resin Research Laboratories

James M. Wyckoff
National Bureau of Standards

Clyde Yates
U.S. Polymeric

Appendix B

Glossary

Abbreviations and Acronyms

ACAP	—Advanced Composite Airframe Program
ACCP	—Advanced Ceramics and Composites Partnership
ACerS	—American Ceramics Society
AIChE	—American Institute of Chemical Engineers
AIST	—Agency of Industrial Science and Technology (Japan)
Al-Li alloys	—aluminum-lithium alloys
AMRF	—Automated Manufacturing Research Facility
ARALL	—aramid-reinforced aluminum composite
ASTM	—American Society for the Testing of Materials
BRITE	—Basic Research in Industrial Technologies for Europe
BMFT	—Ministry for Research and Technology (West Germany)
CAD	—computer-aided design
CAFE	—corporate average fleet fuel economy
CAM	—computer-aided manufacturing
CAMDEC	—Ceramic Advanced Manufacturing Development and Engineering Center
CARE	—Ceramic Applications for Reciprocating Engines (United Kingdom)
CBC	—chemically-bonded ceramic
CMC	—ceramic matrix composite
CNC machines	—computer numerically controlled machine tools
CNRS	—Centre Nationale de la Recherche Scientifique (France)
CoCom	—Coordinating Committee for Multilateral Export Controls
CoGSME	—Composites Group of the Society of Manufacturing Engineers
COMAT	—Committee on Materials
CVD	—chemical vapor deposition
DAR	—Defense Acquisition Regulations
DARPA	—Defense Avanced Research Projects Agency
DoD	—U.S. Department of Defense
DOE	—U.S. Department of Energy
DTI	—Department of Trade and Industry (United Kingdom)
DTIC	—Defense Technical Information Center
EAP	—Experimental Aircraft Program
EAR	—Export Administration Regulations
EC	—European Community
EFA	—European Fighter Aircraft
EG	—electrogalvanization
ELISA	—Export License Status Advisor
ERC	—Engineering Research Center
EURAM, EURAM II	—European Research on Advanced Materials Programs
EUREKA	—a European cooperative research program
FAA	—Federal Aviation Administration
FAR	—Federal Acquisition Regulations
FDA	—Food and Drug Administration
FMS	—Federation of Materials Societies
FRP	—fiber-reinforced plastics
GIRI	—Government Industrial Research Institutes (Japan)
GlFRP	—glass fiber-reinforced plastic
GNP	—Gross National Product
GPa	—gigapascal (billions of newtons per square meter)
GrFRP	—graphite fiber-reinforced plastic
HIP	—hot isostatic pressing
HPC	—high-performance ceramics
HSLA	—high-strength, low-alloy steel
HSRTM	—high-speed resin transfer molding
IDE	—investigational device exemption
IEA	—International Energy Agency
IOP-TK	—Innovation-Oriented Research Program—Technical Ceramics (Netherlands)
IR&D	—Independent Research and Development
IRSIA	—Institute for the Encouragement of Scientific Research in Industry and Agriculture (Belgium)

ITAR	—International Traffic in Arms Regulations
ITPA	—Industrial Technology Promotion Association
IVL	—individual validated license
JAPATIC	—Japan Patent Information Center
JDB	—Japan Development Bank
JFCA	—Japan Fine Ceramics Association
JFCC	—Japan Fine Ceramics Center
JITA	—Japan Industrial Technology Association
JRDC	—Japan Research and Development Corporation
ksi	—thousand pounds per square inch
LCP	—liquid crystal polymer
LEFM	—linear elastic fracture mechanics
ManTech Program	—Manufacturing Technologies Program
MAP	—Manufacturing Automation Protocol
MDF cement	—macro-defect free cement
MITI	—Ministry of International Trade and Industry (Japan)
MMC	—metal matrix composite
MPa	—megapascal (millions of newtons per square meter)
Msi	—millions of pounds per square inch
NACRA	—National Applied Ceramic Research Association
NASA	—National Aeronautics and Space Administration
NASP	—National Aerospace Plane
NBS	—National Bureau of Standards
NC machines	—numerically controlled machine tools
NCMC	—National Critical Materials Council
NDT, NDE	—nondestructive testing, nondestructive evaluation
NIRIM	—National Institute for Research on Inorganic Materials (Japan)
NRDC	—National Research and Development Corporation (United Kingdom)
NSF	—National Science Foundation
NTIS	—National Technical Information Service
OTA	—Office of Technology Assessment
PAN	—polyacrylonitrile
PBT	—poly (phenylbenzobisthiazole)
PEEK	—polyether etherketone
PES	—polyether sulfone
PET	—polyethyleneterephthalate
PMC	—polymer matrix composite
PPS	—polyphenylene sulphide
PVD	—physical vapor deposition
R&D	—research and development
RANN Program	—Research Applied to National Needs Program
RIM	—reaction injection molding
RST	—rapid solidification technology
RTM	—resin transfer molding
SAE	—Society of Automotive Engineers
SACMA	—Suppliers of Advanced Composite Materials Association
SAIC	—Science Applications International Corporation
SAMPE	—Society for the Advancement of Material and Process Engineering
SBIR Program	—Small Business Innovation Research Program
SDI	—Strategic Defense Initiative
SIC code	—Standard Industrial Classification code
SME	—Society of Manufacturing Engineers
SMC	—sheet molding compound
SPE	—Society of Plastics Engineers
SPI	—Society of the Plastics Industry
SPIE	—Society of Photo-Optical Instrumentation Engineers
SSRI	—Swedish Silicate Research Institute
STA	—Science and Technology Agency (Japan)
STELA	—System for Tracking Export License Applications
USACA	—United States Advanced Ceramics Association
VAMAS	—Versailles Project on Advanced Materials and Standards

Glossary of Terms

ablative materials: Materials that protect the structure of aircraft or missiles from the high temperatures generated by air friction by themselves becoming melted or vaporized.

adiabatic: Referring to any process in which there is no gain or loss of heat.

advanced ceramics: Ceramics made from extremely pure starting materials and consolidated at high temperatures to yield dense, durable structures.

advanced composites: Polymer matrix composites reinforced with continuous fibers, usually graphite, aramid, or high-stiffness glass; these composites generally have high strength and stiffness, light weight, and are relatively expensive.

advanced materials: Materials that are built up from constituents and whose properties are tailored to meet the requirements of specific end uses.

aggregate: Inert filler material such as sand or gravel used with a cementing medium to form concrete or mortar.

alloy: A material having metallic properties and consisting of two or more elements.

anisotropic: Showing different physical or mechanical properties in different directions.

aramid: Lightweight polyaromatic amide fibers having excellent high temperature, flame, and electrical properties. These fibers are used as high-strength reinforcement in composites.

axial: In advanced composites, referring to the direction parallel to the orientation of the continuous fiber reinforcement.

bioceramics or biomaterials: Ceramics or other materials that are compatible with biological tissues, and that therefore can be used inside the body.

brittle fracture: A break in a brittle material due to the propagation of cracks originating at flaws.

carbon/carbon composites: Composites consisting of pyrolyzed carbon matrices reinforced with carbon fibers; with appropriate coatings to prevent oxidation, these composites are capable of withstanding extremely high temperatures.

carbon/graphite: These fibers, which are the dominant reinforcement in "advanced" composites, are produced by pyrolysis of an organic precursor, e.g. polyacryonitrile (PAN), or petroleum pitch, in an inert atmosphere. Depending on the process temperature, fibers having high strength or high elastic modulus may be produced.

cement: A dry powder made from silica, alumina, lime, iron oxide, and magnesia that forms a hardened paste when mixed with water; it may be used in this form as a structural material, or used as a binder with aggregate to form concrete.

ceramic: An inorganic, nonmetallic solid.

ceramic matrix composite: A composite consisting of a ceramic matrix reinforced with ceramic particulates, whiskers, or fibers.

charge pattern: The pattern of resins and reinforcements introduced into a mold prior to the molding process.

chemically-bonded ceramics: Used here to distinguish advanced cements and concretes, which are consolidated through chemical reactions at ambient temperatures (generally involving uptake of water) from high performance ceramics, such as silicon nitride and silicon carbide, which are densified at high temperatures.

coefficient of thermal expansion: The change in volume of a material associated with a 1 degree increase in temperature.

composite: Any combination of particles, whiskers, or fibers in a common matrix.

compressive stress: A stress that causes an elastic body to shorten in the direction of the applied force.

concrete: A mixture of aggregate, water, and a binder (usually portland cement) that hardens to a stonelike condition when dry.

consolidation of parts: Integration of a number of formerly discrete parts into a single part that encompasses several functions; a key advantage of engineered materials such as ceramics and composites.

continuous fiber: A reinforcing fiber in a composite that has a length comparable to the dimensions of the structure.

creep: A time-dependent strain of a solid, caused by stress.

critical material: A material whose availability is considered to be extremely important in time of national emergency or for the economic well-being of a nation.

cross-linking: The formation of chemical bonds between formerly separate polymer chains.

crystal: A homogeneous solid in which the atoms or molecules are arranged in a regularly repeating pattern.

curing: Process in which thermosetting resins are converted by chemical reactions into solid, crosslinked structures; usually accomplished by the application of heat and pressure.

deflection: Deformation of a material produced without fracture.

deformation, plastic deformation: Any alteration of shape or dimensions of a body caused by stresses, thermal expansion or contraction, chemical or metallurgical transformations, or shrinkage and expansion due to moisture change.

delamination: Separation of a layered structure into its constituent layers.

dielectric: A material that is an electrical insulator or in which an electric field can be sustained with a minimum dissipation in power.

diffusion: The movement of mass, in the form of discrete atoms or molecules, through a medium.

dispersion: Finely divided particles of one material held in suspension in another material.

dual-use technology: A technology with both military and commercial applications.

ductility: The ability of a material to be plastically deformed by elongation without fracture.

E-glass: A borosilicate glass most used for glass fibers in reinforced plastics.

elasticity: The property whereby a solid material deforms under stress but recovers its original configuration when the stress is removed.

extrusion: A process in which a hot or cold semisoft solid material, such as metal or plastic, is forced through the orifice of a die to produce a continuously formed piece in the shape of the desired product.

failure: Collapse, breakage, or bending of a structure or structural element such that it can no longer fulfill its purpose.

fatigue: Failure of a material by cracking resulting from repeated or cyclic stress.

fiber-reinforced plastic: An inexpensive, relatively low-strength composite usually consisting of short glass fibers in a polyester or vinylester matrix; to be distinguished from an advanced composite.

filtration: A process of separating particulate matter from a fluid, by passing the fluid carrier through a medium that will not pass the particulates.

flexure: Any bending deformation of an elastic body in which the points originally lying on any straight line are displaced to form a plane curve.

fracture stress: The minimum stress that will cause fracture, also known as fracture strength.

glass: A state of matter that is amorphous or disordered like a liquid in structure, hence capable of continuous composition variation and lacking a true melting point, but softening gradually with increasing temperature.

glass-ceramic: Solid material, partly crystalline and partly glassy, formed by the controlled crystallization of certain glasses.

grain: One of many crystallites comprising a polycrystalline material.

green state, greenware: A term for formed ceramic articles in the unfired condition.

hardness: Resistance of a material to indentation, scratching, abrasion, or cutting.

heat exchanger: A device that transfers heat from one fluid to another or to the environment, e.g. an automobile radiator.

heat treatment: Heating and cooling of a material to obtain desired properties or conditions.

high-strength low-alloy steel: Steel containing small amounts of niobium or vanadium, and having superior strength, toughness, and resistance to corrosion compared with carbon steel.

holography: A technique for recording and later reconstructing the amplitude and phase distributions of a wave disturbance.

hot isostatic pressing: A forming or compaction process for ceramic or metal powders in which the mold is flexible and pressure is applied hydrostatically or pneumatically from all sides.

hot pressing: Forming a metal powder compact or a ceramic shape by applying unidirectional pressure and heat simultaneously at temperatures high enough for sintering to occur.

impact strength: Ability of a material to resist shock loading.

inclusion: A flaw in a material consisting of a trapped impurity particle.

injection molding: Forming metal, plastic, or ceramic shapes by injecting a measured quantity of the material into shaped molds.

internal stress, residual stress: A stress system within a solid (e.g. thermal stresses resulting from rapid cooling from a high temperature) that is not dependent on external forces.

interphase, interface: The boundary layer between the matrix and reinforcement in a composite.

joining: Coupling together of two materials across the interface between them, e.g. through application of adhesives, welding, brazing, diffusion bonding, etc.

lay-up: A process for fabricating composite structures involving placement of sequential layers of matrix-impregnated fibers on a mold surface.

load: The weight that is supported by a structure, or mechanical force that is applied to a body.

Mach number: The ratio of the speed of a body to the speed of sound in the surrounding fluid.

matrix: The composite constituent that binds the reinforcement together and transmits loads between reinforcing fibers.

merchant market: The market for intermediate components or materials that can be used in the manufacture of a variety of finished systems.

metal: An opaque material with good electrical and thermal conductivities, ductility, and reflectivity;

properties are related to the structure in which the positively charged nuclei are bonded through a field of mobile electrons which surrounds them, forming a close-packed structure.

metal matrix composite: Composite having a metal matrix (often aluminum) reinforced with ceramic particulates, whiskers, or fibers.

microstructure: The internal structure of a solid viewed on a distance scale on the order of micrometers. The microstructure is controlled by processing, and determines the performance characteristics of the structure.

mini-mills: Steel producers using electric furnaces to generate commodity-grade bar and rod products from steel scrap; to be distinguished from integrated mills, which produce steel products from basic raw materials.

modulus of elasticity: A parameter characterizing the stiffness of a material, or its resistance to deformation under stress. For example, steel has a relatively high modulus, while Jello has a low modulus.

monolithic: Constructed from a single type of material.

near-net-shape The original formation of a part to a shape that is as close to the desired final shape as possible, requiring as few finishing operations as possible.

nondestructive testing, evaluation: Any testing method that does not involve damaging or destroying the test sample; includes use of x-rays, ultrasonics, magnetic flux, etc.

offset: Agreement by which the seller of a high-technology product transfers relevant production technology to the buyer as a condition of the sale.

phase: A region of a material that is physically distinct and is homogeneous in chemical composition.

pitch: A complex mixture of partially-polymerized aromatic hydrocarbons derived from heat treatment of coal or petroleum; can be spun into a fiber and pyrolyzed to produce graphite.

plasticity: The property of a solid body whereby it undergoes a permanent change in shape or size when subjected to a stress exceeding a particular value, called the yield value.

polyacrylonitrile: Organic precursor that can be spun into fibers and pyrolized to produce graphite fibers.

polymer: Substance made of giant molecules formed by the union of simple molecules (monomers); for example, polymerization of ethylene forms a polyethylene chain.

polymer matrix composite: Composite consisting of an organic, polymeric matrix reinforced with particulates, short fibers, or continuous fibers.

pore, porosity: Flaw involving unfilled space inside a material that frequently limits the material strength.

powder metallurgy: Referring to the fabrication of metallic shapes by compressing metal powders and applying heat without melting to produce a dense, durable structure.

precursor: An intermediate material that can be converted to the final desired material by a chemical reaction, often at high temperatures.

preform: A compact of fibers in the shape of the final structure that is placed in a mold and impregnated with the matrix to form a composite.

prepreg: Fiber reinforcement form (usually tape, woven mat, or broadgoods) that has been preimpregnated with a liquid thermosetting resin and cured to a viscous second stage. Thermoplastic prepregs are also available.

proof test: A predetermined test load, greater than the intended service load, to which a specimen is subjected before acceptance for use.

qualification: Formal series of tests by which the performance and reliability of a material or system may be evaluated prior to final approval or acceptance.

radiography: The technique of producing a photographic image of an opaque specimen by transmitting a beam of x-rays or gamma rays through it onto an adjacent photographic film; the transmitted intensity reflects variations in thickness, density, and chemical composition of the specimen.

radome: A strong, thin shell made from a dielectric material, used to house a radar antenna.

reciprocating (engine or machinery): Having a motion that repeats itself in a cyclic fashion.

reexport controls: Requirements that foreign-based firms wishing to export certain U.S. technologies to third countries must apply to the United States for a license to do so.

refractory: Capable of enduring high temperature conditions.

resin: Organic polymer, usually a viscous liquid, that can be processed to yield a solid plastic.

scale-up: The conversion of a low-volume laboratory process into a high-volume process suitable for commercial production.

S-glass: A magnesia-alumina-silicate glass that provides high stiffness fiber reinforcement. Often regarded as the reinforcement fiber dividing "advanced" composites from reinforced plastics.

shearing stress: A stress in which the material on one side of a surface pushes on the material on the other side of the surface with a force that is parallel to the surface.

sheet molding compound: An inexpensive, low-strength composite consisting of chopped glass fibers in a polyester matrix, which is produced in sheets that can be compression molded to give the final shape.

sintering: Method for the consolidation and densification of metal or ceramic powders by heating without melting.

slip casting, slip, slurry: A forming process in the manufacture of shaped refractories, cermets, and other materials in which slip is poured into porous plaster molds. Slip or slurry is a suspension of fine clay in water with a creamy consistency.

specific strength or stiffness: The strength or stiffness of a material divided by its density; this property can be used to compare the structural efficiency of various materials.

strain: Change in length of an object in response to an applied stress, divided by undistorted length.

stress: The force acting across a unit area in a solid material in resisting the separation, compacting, or sliding that is induced by external forces.

structural materials: Those materials that support most of the loading on the whole system.

substrate: Base surface on which a material adheres, for example a surface to be coated.

systems approach (to cost or to design): Consideration of product design, manufacture, testing, and life cycle as an indivisible whole; see consolidation of parts.

tensile strength, ultimate tensile strength: The maximum stress that a material subjected to a stretching load can withstand without breaking.

thermal conductivity: The rate of heat flow under steady conditions through unit area per unit temperature in the direction perpendicular to the area; the ability of a material to conduct heat.

thermoplastic resin: A material containing discrete polymer molecules that will repeatedly soften when heated and harden when cooled; for example, polyethylenes, vinyls, nylons, and fluorocarbons.

thermosetting resin: An organic material initially having low viscosity that hardens due to the formation of chemical bonds between polymer chains. Once cured, the material cannot be melted or remolded without destroying its original characteristics; examples are epoxies, phenolics, and polyimides.

toughness: A parameter measuring the amount of energy required to fracture a material in the presence of flaws.

transverse: In advanced composites, referring to the direction perpendicular to the orientation of the continuous fiber reinforcement.

tribology: The study of the phenomena and mechanisms of friction, lubrication and wear of surfaces in relative motion.

turbocharger: A centrifugal air compressor driven by the flow of exhaust gases and used to increase induction system pressure in an internal combustion reciprocating engine.

ultrasonic testing: A nondestructive test method that employs high-frequency mechanical vibration energy to detect and locate structural discontinuities and to measure the thickness of a variety of materials.

unibody: Integrated structure containing the chassis as well as elements of the body of an automobile.

value-added: The increment by which the value of the output of an operation exceeds the value of the inputs.

viscoelasticity: Property of a material that is viscous but that also exhibits certain elastic properties, such as the ability to store energy of deformation, and in which the application of a stress gives rise to a strain that approaches its equilibrium value slowly.

wear: Deterioration of a surface due to material removal caused by friction between it and another material.

wettability: The ability of any solid surface to be wetted when in contact with a liquid.

whisker: A short, single crystal fiber with a length-to-diameter ratio of 10 or more, often used to improve the fracture toughness of ceramics.

yield strength: The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic.

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